A Framework of Multiclass Travel Demand Forecasting and Emission Modelling, Incorporating Commercial Vehicle Movement for the Port City of Halifax, Canada

by

Pauline Laila Bela

Submitted in partial fulfilment of the requirements

for the degree of Master of Applied Science

at

Dalhousie University
Halifax, Nova Scotia
November, 2018

Dedicated to

My Husband, My Inspiration

MD Jahedul Alam

Table of Content

List of Tables

List of Figures

Abstract

This thesis develops a comprehensive Regional Transport Network Modelling framework that generates, distributes and assigns commercial vehicles along with passenger car, and estimates the resulting vehicular emission in Halifax. First, this study presents a four-stage travel demand forecasting model that accommodates truck movement within the 2011 Halifax transport network model. Heavy, medium and light truck trips are generated by utilizing GPS tracking and EPOI information respectively. Later, the model is enhanced by incorporating delivery truck tours for 2016 by utilizing an Info-Canada Business Establishment dataset. The uniqueness of this study is that a novel approach of Monte Carlo simulation technique is used to develop relevant tour attributes for delivery truck. This model also includes trip-rate analysis approach for delineating trip generation of passenger car. Both models are used to estimate vehicular emission of GHG, CO, NOx, $PM_{2.5}$, PM_{10}, SO_2, THC, and VOC. The findings of this study will be beneficial for transportation professionals to develop strategies for traffic management and emission reduction.

List of Abbreviations and Symbols Used

CANUE : Canadian Urban Environmental Health Research Consortium

CO : Carbon Monoxide

CO_2 : Carbon Dioxide

CT : Census Tract

DA : Dissemination Area

DMTI : Desktop Mapping and Technological Inc.

EMME : Equilibre Multimodal Multimodal Equilibrium

EPA : Environmental Protection Agency

EPOI : Enhanced Points of Interest

GEH : Geoffrey E. Havers, Statistics

GHG : Greenhouse Gas

GIS : Geographic Information Systems

GPS : Global Positioning Systems

GSS : General Social Survey

HBO : Home based Other

HBS : Home based School

HBSh : Home based Shopping

HBW : Home based Work

HDDV : Heavy Duty Diesel Vehicle

HMTS : Household Mobility and Travel Survey

HOC : High Occupancy Vehicle

HPA : Halifax Port Authority

HRM : Halifax Regional Municipality

MOVES : Motor Vehicle Emission Simulator

NHB : Non Home based

NHS : National Household Survey

NOx : Nitrogen Oxides

O-D : Origin-Destination

PCE : Passenger Car Equivalent

PM_{10} : Particulate Matter ranging from 2.5 to 10 microns

$PM_{2.5}$: Particulate Matter smaller than 2.5 microns

SO_2 : Sulphur Dioxide

TAZ : Traffic Analysis Zone

THC : Total Hydrocarbon

VDF : Volume Delay Function

VHT : Vehicle Hour Travelled

VKT : Vehicle Kilometers Travelled

VOC : Volatile Organic Compounds

RMSE : Root Mean Square Error

Indices and sets

$c \in C$ = Traffic classes

$o \in O$ = Origin zones

$d \in D$ = Destination zones

$k \in K_{od}^{c}$ = Directed paths linking o and d for class c

$k \in K$ = All directed paths

$j \in J$ = Nodes of the road network

$l \in L$ = Links of the road network

$l_1 \in L_j^-$ = Links "ending" at node j

$l_2 \in L_j^+$ = Links "starting" at node j

Constants

g_{od}^{c} = Traffic demand from o to d for class c (vehicles)

$\overline{v_l}$ = Additional volume on link a (vehicles), *volad*

$\overline{v_{l_1 l_2}}$ = Additional volume on turn $l_1 l_2$ (vehicles), *pvolad*

b_l^c = Fixed link cost (or bias) on link l for class c

δ_{lk} = 1 if link l belongs to path k

$\delta_{l_1 l_2 k}$ = 1 if turn $l_1 l_2$ belongs to path k

Functions

$s_l(v_l)$ = Volume-delay function on link l

$o_{l_1 l_2}(v_{l_1 l_2})$ = Turn penalty function on turn $l_1 l_2$

Variables

v_l = Auto equivalent traffic volume on link l, *volad*

$v_{l_1 l_2}$ = Auto equivalent traffic volume on turn $l_1 l_2$, *pvolad*

v_l^c = Auto equivalent traffic volume on link l for class c

$v_{l_1 l_2}^{c}$ = Auto equivalent traffic volume on turn $l_1 l_2$ for class c

h_k = Flow on path k

Acknowledgements

I would like to thank the almighty Allah for giving me the strengths and blessings in completing this thesis. I would like to express my sincere gratitude to my supervisor, Dr. Muhammad Ahsanul Habib, who is an excellent mentor as well as an idol to follow in every step of life. I am grateful to you for giving me the opportunity to be a part of your Dalhousie Transportation Collaboratory (DalTRAC) research team. Thank you for your immense support, guidance, inspiration and valuable suggestions throughout my research. I am blessed to have a true and caring guardian like you in Canada. Your advices are priceless and significantly helped me to overcome the challenges in my academic career as well as in personal life. I would like to offer my enduring gratefulness to Dr. Nouman Ali and Dr. William Phillips for their valuable contributions, constructive suggestions and their roles in the supervisory committee.

I would like to acknowledge Dr. Hanna Maoh and Kevin Gingerich for providing the necessary data to accomplish this thesis. I am also thankful to my DalTRAC team members, for their cooperation, support and constructive suggestions throughout my research work. I would also like to acknowledge the funding sources: Canadian Urban Environmental Health Research Consortium (CANUE), Natural Sciences and Engineering Research Council of Canada (NSERC), Nova Scotia Department of Energy and Dalhousie University.

Finally, I am very grateful to my husband, Jahed for his unconditional support, encouragement and patience throughout this research. A special thanks to my family for their love, understanding and support during pursuing my academic dream.

Chapter 1

Introduction

1.1 Background and Motivation

Urban transportation system is a fundamental component of modern cities in order to enhance the mobility of passengers and goods in an efficient way. At the same time, it is responsible for the increase in environmental pollution, energy consumption and congestion of urban road networks. Due to sprawling nature of urbanization, an increased volume of single occupant vehicles for commuting is causing emission-related serious public health concerns. Moreover, commercial vehicle plays a vital role in shaping the economy of a city by facilitating the goods movement in and out of the city, which in turn causes congested traffic condition and emission, including Greenhouse Gas emission (GHG). In Canada, transportation sector is the second largest contributor of GHG emission *(Environment Canada, 2014; Environment and Climate Change Canada, 2018)*. Figure 1-1 shows the GHG emission of different economic sectors of Canada from the year of 1990 to 2016. This has been observed that transportation sector has been increasingly contributing to GHG emission. Figure shows that this sector contributes to almost one quarter (24%) of the overall GHG emissions for the country *(Environment Canada, 2014; Behan et al., 2008)*. Between 1990 and 2016, GHG emissions from the transportation sector grew by 42% *(Environment and Climate Change Canada, 2018)*. However, the more concerning issue is the rising trend of emission from commercial vehicles over the year. Figure 1-2 shows the distribution of GHG emission for transportation sectors of Canada. The statistics reveals that passenger car emission dropped by 2016 due to continuous improvements in the fuel efficiency *(Natural Resources Canada, 2018).*

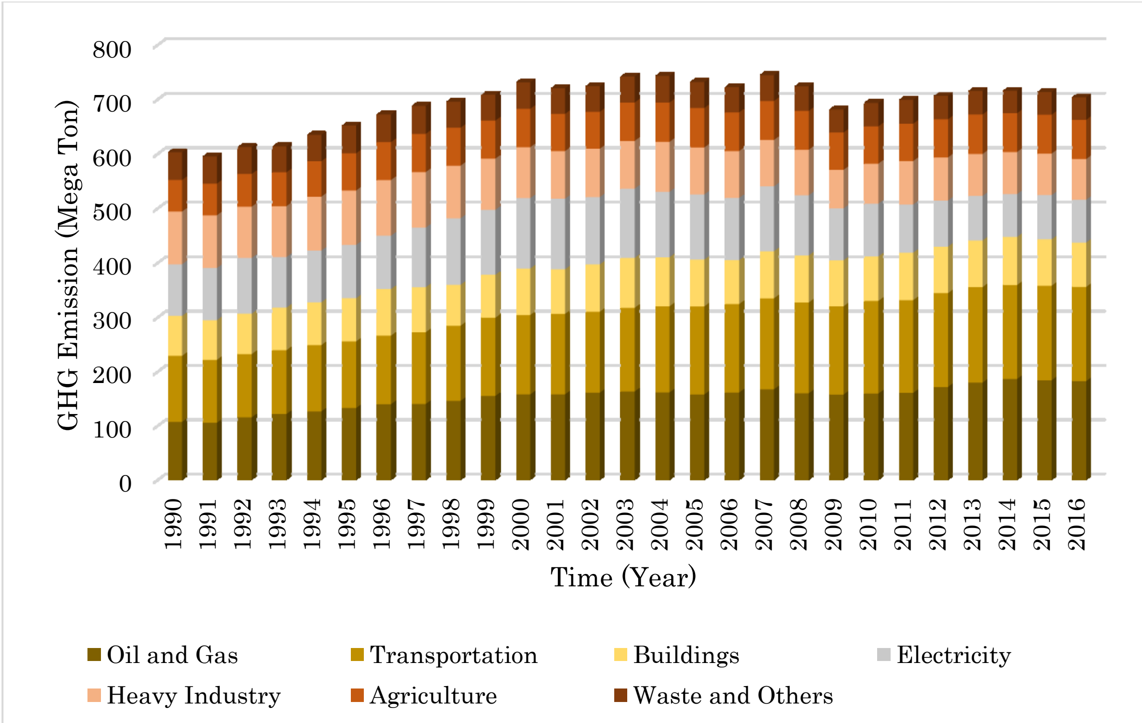


Figure 1-1 GHG Emissions by Economic Sectors of Canada, 1990 to 2016

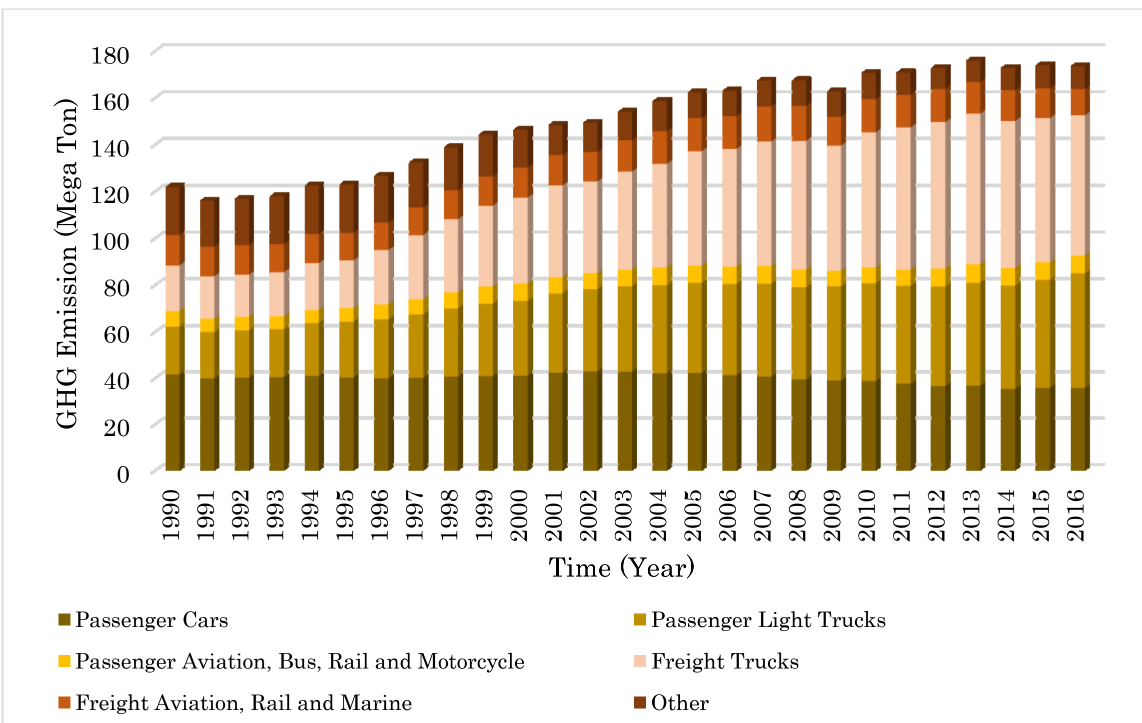


Figure 1-2 GHG Emissions from Transportation Sector of Canada, 1990 to 2016

In contrast, GHG emission from commercial vehicles (both light trucks and freight trucks) keeps increasing from 1990 to 2016. Nevertheless, passenger travel demand analysis received a substantial attention in the existing literature, while equal importance is not paid to commercial vehicle in the realm of travel demand forecasting modeling. Consequently, developing reliable prediction of future travel demand seems to be problematic. Therefore, it warrants to develop a travel demand forecasting modeling framework considering both the passenger and commercial vehicle movement in tandem.

1.2 Overall Goal

The overarching goal of these research project is to develop an improved multiclass transport network model for Halifax which includes commercial vehicle along with passenger car movements. The goal of this study clearly aligns with the objectives of the Canadian Urban Environmental Health Research Consortium (CANUE), which aims to build a national environmental exposure data platform for integrated analyses of urban form and health. The scientific objectives of CANUE are (1) to develop integrated models of multiple harmful and protective characteristics of the physical environment in urbanized areas and how they interact to influence individual behavior and health during different stages of the life course, (2) to identify specific features of a health-promoting urban form for Canadian cities of today and tomorrow in the context of reducing carbon emissions and building resilience to the effects of a changing climate, and (3) to increase the understanding of susceptibility (cultural, socioeconomic, genetic, age, gender, behavioral) to refine risk assessment, target intervention and lay the foundation for personalized health.

As a part of attaining the objectives of CANUE, this study will develop a modelling framework for the estimation of travel demand and emission to provide transportation related data for CANUE researchers (as a broader goal). Specifically, the outcome of this study will include link flow for different vehicle classes with different fuel types and emission estimates for major pollutants: Greenhouse gas (GHG), carbon monoxide (CO), nitrogen oxides (NOx), particulate matter smaller than 2.5 µm ($PM_{2.5}$), particulate matter ranging from 2.5 to 10 µm (PM_{10}), sulphur dioxide (SO_2), total hydrocarbons (THC), and volatile organic compounds (VOC). To accomplish these tasks, this study will attain four specific objectives which are described in the following section.

1.3 Specific Objectives

The specific objectives of this thesis are:

- To develop a regional modelling framework for multiclass transport network model that incorporates commercial vehicle movements in combination with passenger car movement
- To develop a tour-based local delivery truck movement model to enhance the multiclass transport network model.
- To estimate traffic flows and emission by utilizing the results obtained from the regional multiclass transport network model
- To evaluate vehicular emissions of major pollutants at the Port City of Halifax

1.4 Scope of Work

Based on the motivation of this research, this study contributes to develop a sequential and comprehensive travel and emission modelling framework that combines a regional transport network model with an emission estimation platform. An extensive literature review of current practice of travel demand modeling and emission modeling has been conducted in this study. It focuses on the quantification and in-depth analysis of the environmental pollutants.

The modelling framework of the research will be useful for traffic management, air quality monitoring and policy making.

1.5 Structure of the Thesis

This thesis is structured in five chapters. The first chapter explains the background motivation and presents the research objectives and the structure of the thesis. The second chapter develops a trip-based multiclass travel demand modeling for Halifax Regional Municipality (HRM) incorporating commercial vehicle movements. This chapter conducts an extensive literature review on four stage travel demand modelling, commercial vehicle travel demand modelling network development, detailed modelling approach, and results of multiclass traffic assignment for the year of 2011. The third chapter presents an enhanced travel demand model of HRM for the year of 2016. This model includes trip-based travel demand model for passenger car and a tour-based approach for local delivery truck model as well as long haul truck movements. In the fourth chapter, two emission models are developed from the results of previous two model. This chapter illustrates different analysis for evaluation of emission for the year of 2011 and 2016. The last chapter summarizes the thesis including its contributions, limitations, recommendations for the future research and some policy implications. Figure 1-3 illustrates the thesis chapters and their interactions.

This study integrates a multiclass traffic network model developed within the Equilibre Multimodal Multimodal Equilibrium (EMME) platform with an emission modelling framework based on Motor Vehicle Emission Simulator (MOVES), developed by the US Environmental Protection Agency (EPA). The first two models provide the emission model with necessary inventories (i.e. VKT, speed distribution, vehicle type fraction) for estimating the emission of major air pollutants: Greenhouse gas (GHG) as CO_2-equivalent, carbon monoxide (CO), nitrogen oxides (NOx), particulate matter smaller than 2.5 μm

($PM_{2.5}$), particulate matter ranging from 2.5 to 10 μm (PM_{10}), sulphur dioxide (SO_2), total hydrocarbons (THC), and volatile organic compounds (VOC) and in traffic analysis zones (TAZs) level for the Halifax Regional Municipality (HRM).

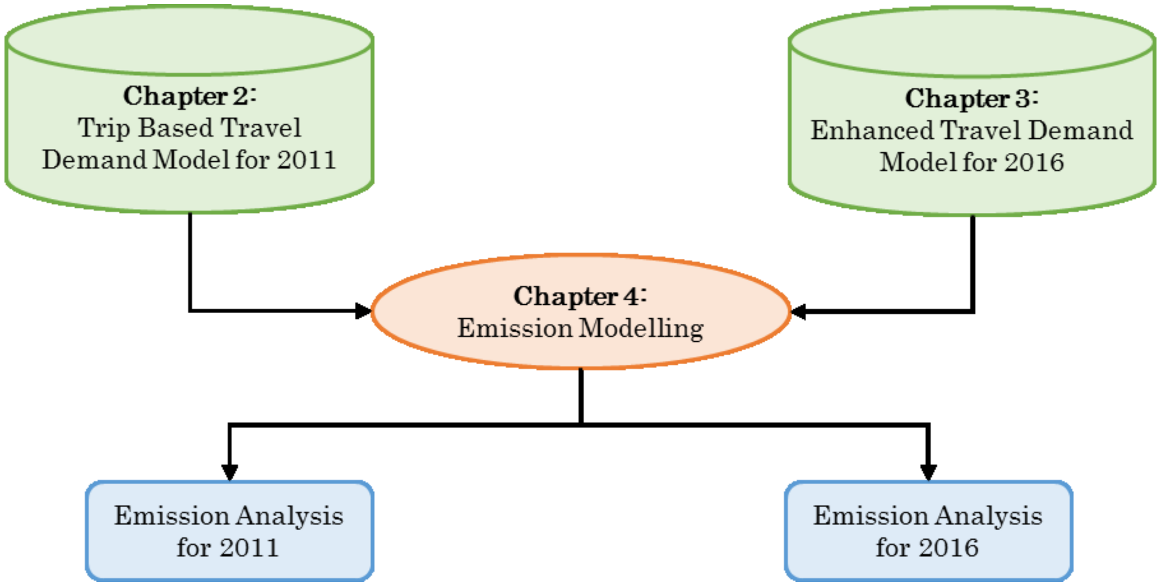


Figure 1-3 Thesis Structure and Connection of Chapters

Chapter 2

Development of a Trip-based Regional Transport Network Model[1]

2.1 Introduction

Development of a multiclass travel demand forecasting model is critical to estimate passenger and freight demand and traffic congestion in the transport network. A regional transport network model is an effective planning tool to evaluate the alternatives for infrastructure planning and environmental assessment studies, land use policies, programs, and projects *(Hunt and Stefan, 2007)*. In urban areas, along with enormous number of passenger car flows, a substantial portion of the traffic movements are made by commercial vehicles to deliver goods and services. Generally, trips intended to serve commercial purposes comprise 10–15% of the total trips in an urban area *(Hunt and Stefan, 2007).* The commercial vehicle movement is even more critical in a port city, such as Halifax, located in the Atlantic coast of Canada.

Halifax, the capital of Nova Scotia, has two container terminals and one intermodal terminal in its downtown core and experiences a daily high truck traffic flow during the peak hours *(Halifax Inland Terminal and Trucking Options Study, 2006)*. The Port of Halifax is one of Canada's largest commercial ports and is known as Atlantic gateway to Canada. The Halifax Harbor never freezes, making it accessible to ships all year round. The

[1] This chapter is largely derived from the peer-reviewed conference paper, Bela, P. L., and Habib, M. A. (2018). "Urban Freight Network and Emission Modeling for Port City Halifax, Canada: A Spatial and Temporal Evaluation of Commercial Vehicles Movement". *Proceedings of the 97th Annual Meeting of Transportation Research Board*, Washington, D. C., January 7-11, (No. 18-06689)

strategic location of the port, efficient, modern infrastructures, and world class security have made it one of the most desirable ports in North America *(Canada's Big 4 Container Ports, 2013).* Although rail carries a portion of freight in Halifax, trucks are still a predominant mode for commercial goods movement. This large truck flow significantly contributes to the local traffic congestion and environmental pollution of the city. The situation becomes even worse when the commercial vehicles add to the existing daily commuter traffic, resulting in an increase in traffic operation challenges during the peak hours. Interestingly, there is no current regional travel demand forecasting model that considers commercial vehicle in combination with passenger cars. In this context, development of a travel demand forecasting model that can incorporates commercial vehicles in combination with other modes is of paramount importance, especially for this region of Nova Scotia.

Therefore, this chapter presents the development of a large-scale multiclass travel demand forecasting model that generates, distributes and assigns trucks with passenger car in the Halifax transport network. The multiclass transport network model is developed within the Equilibre Multimodal Multimodal Equilibrium (EMME) platform. The model is calibrated and validated utilizing the observed traffic count data obtained from Halifax Regional Municipality (HRM) for morning, mid-day, and evening peak periods.

2.2 Literature Review

In many large cities, municipality planners and engineers find the travel demand forecasting model as an effective planning tool for making policy decisions. In Toronto, Greater Golden Horseshoe (GGH) Model has been developed in 2009 to forecast passenger and freight demand on the transportation network for the morning and afternoon peak periods. The model predicts travel demand for the entire GGH area, covering both periods. Previous model covered the Greater Toronto and Hamilton Area (GTHA), which dealt with a single peak period and captured the interaction between the GGH and GTHA with the external zones *(IBI Group, 2009b).* McMaster Institute for Transportation and Logistics (MITL) developed a model to generate origin-destination matrices of only commercial vehicle movement in Greater Toronto-Hamilton Area *(Area, 2010).* Jansuwan et al. *(2013)* developed a simplified travel demand forecasting tool, which offers applications of four stage travel demand modeling specifically targeting small cities, like Utah. Other travel demand forecasting models include Delaware Department of Transportation (DelDOT)'s statewide travel demand model encompassing state of Delware and nine counties of Marryland's eastern shore *(Thompson-Graves et al., 2006),* statewide integrated model (SWIM) commissioned by Oregon Department of Transportation (ODOT) *(Weidner et al., 2009; Hunt et al., 2001; Parsons Brinckerhoff Quade and Douglas, Inc, 1999; Parsons Brinckerhoff Quade and Douglas, Inc, 2000).*

Although, development of large-scale models has grown over the last two decades, truck has been underrepresented in travel demand modeling research. Travel demand modeling generally focuses on personal trips which is not surprising at all. The reason can be realized from a statistic in USA that only 4.1% of total vehicle kilometer traveled is generated by trucks *(U.S. Department of Transportation, 2013).* However, road damage caused by a heavy truck is 1000 times the damage caused by a car *(Small et al., 1989)*. Moreover, in near future, the current growth in freight transportation is going to outrun the growth in passenger transportation *(Chow et al., 2010)*. Several studies, for instance, the Southern California Association of Governments (SCAG) developed a methodology to determine the travel demand of heavy-duty truck and associated emission for the SCAG Regional Model *(Meyer Mohaddes Associates Inc., 1998).* The Phoenix Metropolitan area in USA developed a model that uses both the trucks and cars for commercial movement *(Ruiter, 1992)*. However, these models lack an assignment component that considers personal trip in tandem with the commercial vehicle trips. In another word, a multiclass traffic assignment that includes passenger cars and commercial vehicles within a regional transport network modeling platform is limited *(Beagan et al., 2007).*

Therefore, this chapter develops travel demand models for both the passenger cars and commercial vehicles and analyzes the demand pattern spatially and temporally within the HRM transport network. This chapter also provides link-based classified traffic flows for cars and different truck types from a single traffic assignment which provides necessary inputs for an emission estimation model as described in Chapter 4.

2.3 Modelling Approach

This study develops a regional travel demand forecasting model following four steps such as (i) trip generation by cars and trucks, (ii) distribution of trips, (iii) mode choice modeling, and (iv) assignment of passenger cars and trucks simultaneously within a single traffic assignment platform. Figure 2-1 illustrates different components of the developed travel demand forecasting model as well as the interactions between them. The model outputs the link-based traffic volumes by modes, travel times, average speed and other traffic flow indicators at an hourly interval.

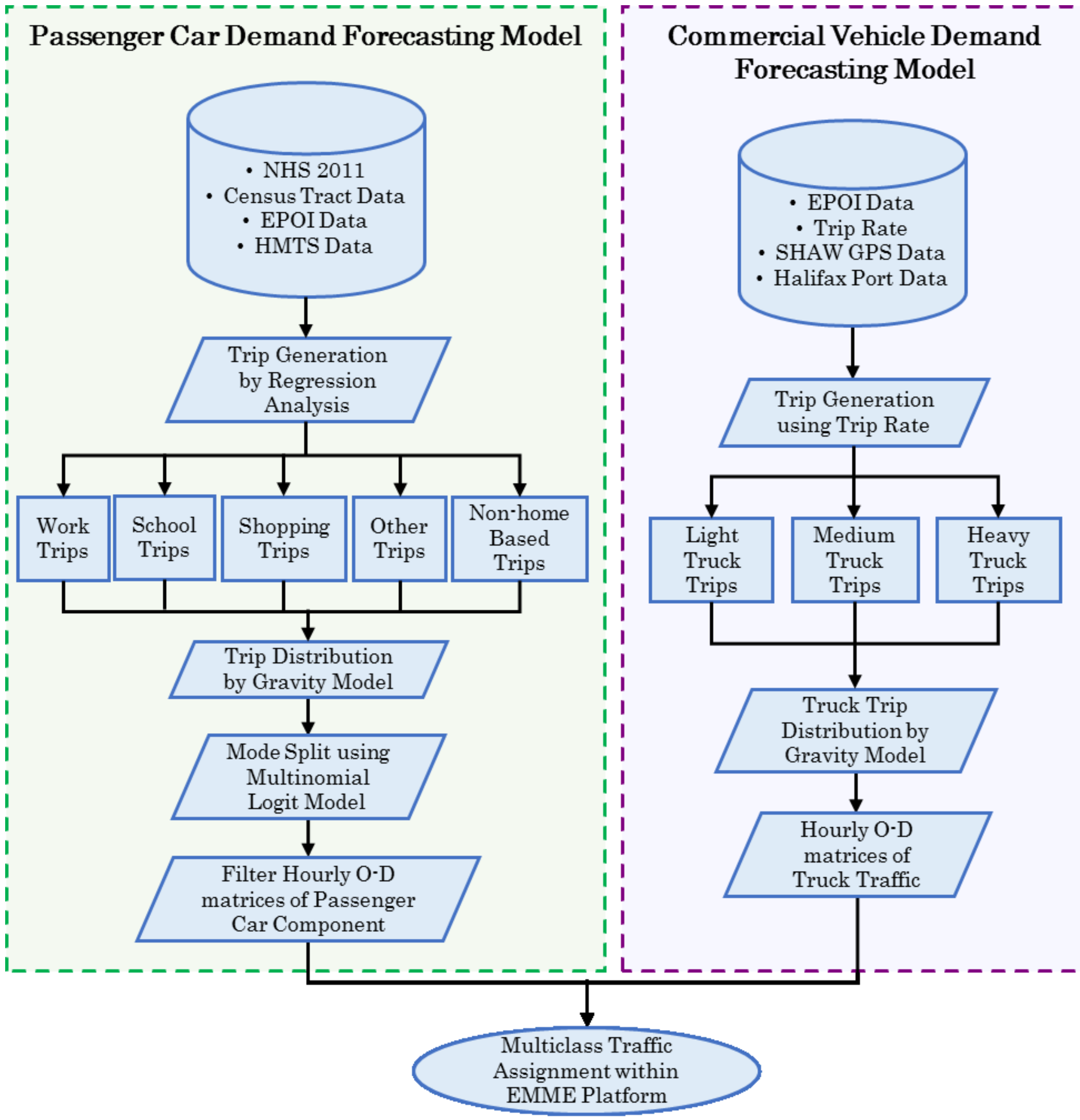


Figure 2-1 Framework of Travel Demand Model for the Year of 2011

2.3.1 Study Area

This Study considers Halifax, the capital of Nova Scotia, Canada as the study area. According to 2011 Census data, total number of individual residents in Halifax is 390,308. The geographic unit of the census data collection is the smallest zonal-level of dissemination area (DA). This study area includes in total 601 DAs.

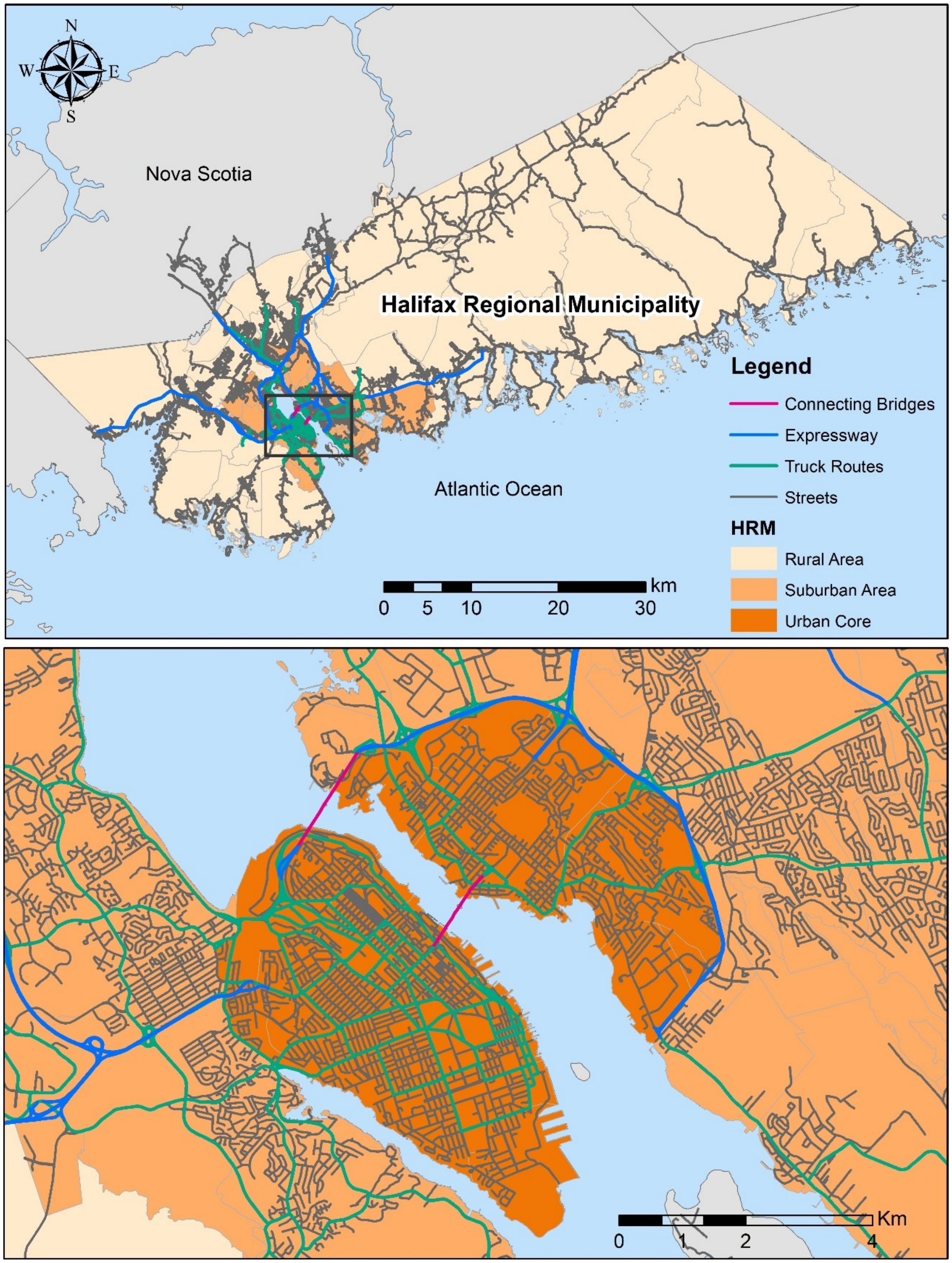


Figure 2-2 Study Area and Road Network of Halifax

This study area covers approximately an area of 5,577 km^2 having a total 2686.67 km (1669.42 mile) of road network. Robie Street, Young Street, Barrington Street, Spring Garden Road, Quinpool Road, Chebucto Road, Mumford Road, Bayers Road are the major roads within this port City. Halifax has two ports within its busiest downtown core area. Located on one of the largest and deepest natural harbors in the world, this is a major port area for shipping companies with connections to over 150 countries *(Halifax Port Authority, 2016)*. The two main container ports owned by the Halifax Port Authority are the Fairview Cove Terminal (Terminal size: 70 acres; capacity: 780,000 standard container) and the South End Terminal (Terminal size: 74.5 acres; capacity: 750,000 standard container) *(Halifax Port Authority, 2016)*. Both ports are connected by major truck routes (Figure 2-2) and CN Rail lines *(Halifax Port Authority, 2016)*. Almost all roads in Halifax allow passenger cars with restrictions for truck traffic. Some road segments prohibit trucks, others have restriction for night time use only (from 9pm to 7am). Only a few major connector roads allow truck traffic 24 hours per day. A representation of study area with existing transport network for Halifax is presented in Figure 2-2. The urban core of Halifax is concentrated around its downtown and has a mix of commercial, residential, and office use. Suburban areas are around the periphery of the urban areas and include mostly residential uses with some industrial and commercial areas. Rural areas are further outspreaded from the Halifax peninsula.

2.3.2 Traffic Analysis Zone System for the Halifax Network Model

Traffic analysis zone (TAZ) is a geographic unit of regional transport network modelling and is used for data collection, tabulation, and analysis. Defining a TAZ system is an early step in the development of any travel demand forecasting modeling. Very often, socio-demographic, and land use information including household size, automobiles per household, household income, and employment characterize the TAZ *(Riad, 2018; Yan and Habib, 2011; Burgess,* *2010; Martin and McGuckin, 1998)*. TAZ represents the origin and the destination of travel activity in an area *(Martin and McGuckin, 1998)*. Spatial data helps to better understand the pattern of trip production and attraction within the TAZ boundary. Relatively small-sized TAZ provides better representation of the travel activities and socio-demographic characteristics than those larger in size. In that case, the computational cost grows higher due to the large number of TAZs. Halifax Regional Municipality developed a travel demand model of 88 TAZs which was compatible with census tract boundaries *(Burgess, 2010)*. However, the zonal boundaries did not well comply with the road network and land uses *(Yan and Habib, 2011)*. To improve the existing TAZ system, Yan and Habib *(2011)* developed a zonal system for Halifax with 206 traffic analysis zones. This study extends this zonal system with 222 TAZs that includes 92 urban, 95 suburban, 32 rural and 3 external zones (Figure 2-3). External zones are created to represent the heavy traffic activity between the HRM and outside the HRM specifically for capturing truck movement. Three external zones located at Truro, Windsor and Bridgewater are considered to capture the external-internal and/or internal-external movements of long-haul heavy trucks for highway 102, 101 and 103 bound traffic respectively. Trucks can deliver goods in Cape Breton, Prince Edward Island, other parts of Canada and/or outside of Canada through Truro. The southwestern area of Nova Scotia can be served through two other external zones. Regional transport network modeling requires coding of these TAZs and road network with their physical and operational characteristics. The following section describes network representation within the traffic assignment platform.

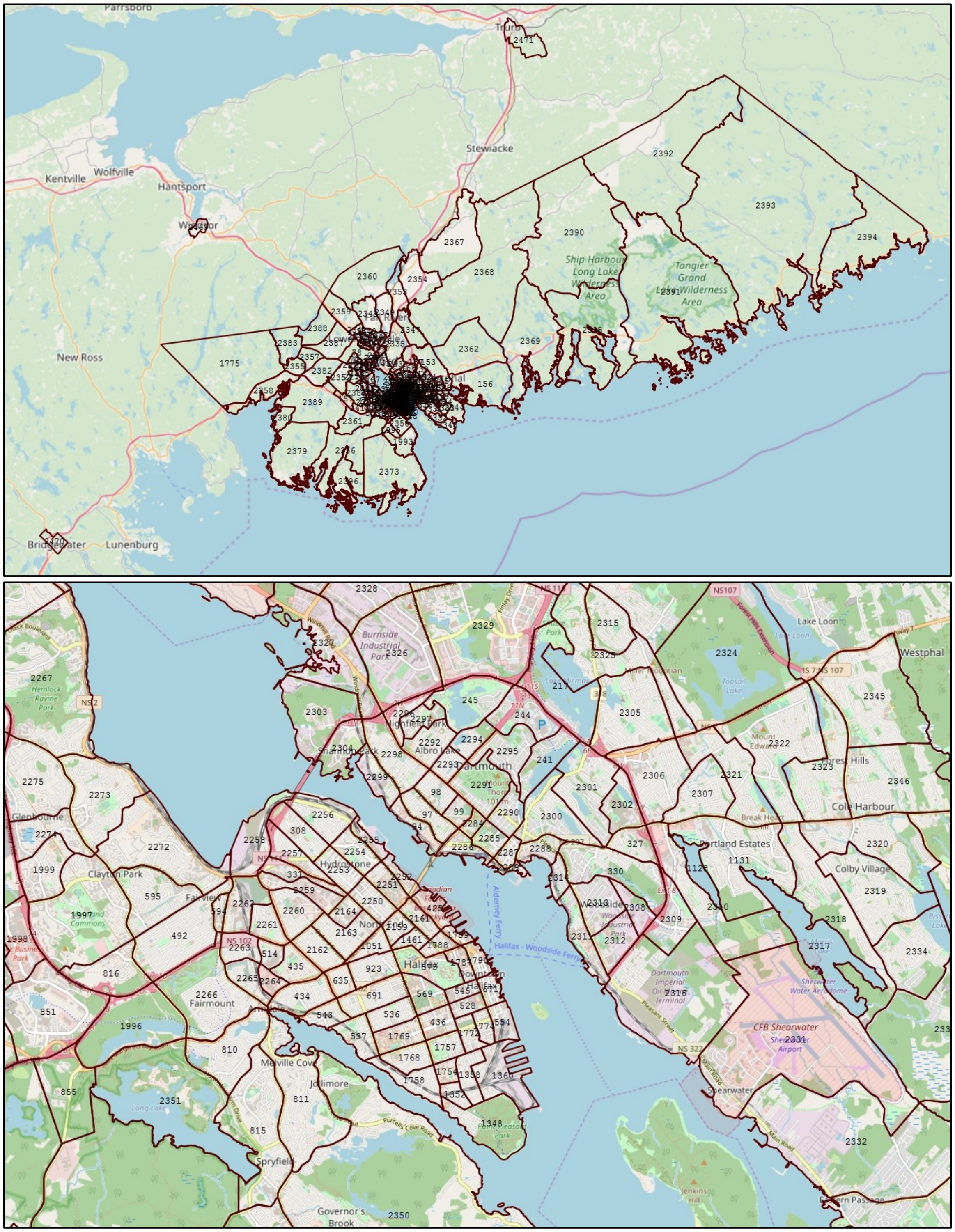


Figure 2-3 Traffic Analysis Zones (TAZs) of Halifax Regional Municipality

Table 2-1 Details of TAZs within the Halifax Transport Network Model

TAZs	Number of TAZs	Area (km^2)				Total Population	
		Minimum	Average	Maximum	Total	2011	2016
Urban Core	92	0.09	0.37	1.18	34.3	89,389	95,537
Suburban Area	95	0.26	4.95	86.43	470.6	214,550	220,069
Rural Area	32	13.17	167.33	1113.52	5354.6	86,369	86,550
External	3	-	-	-	-	-	-

2.3.3 Road Network Representation

This study has coded the entire Halifax transport network within the EMME/4 platform. EMME provides an interactive computing environment that allows mapping, network editing, scenario-based data management and scenario comparison. The network includes nodes, links, zonal centroids, connectors, ports, bridges, and highways within HRM. Halifax Geodatabase 2012 is used to visually build the Halifax regional transport network. Google Street View is used for verification purpose. Both passenger car and trucks share this common road network, with congested travel times based on the combined vehicle flow. Three external zones are considered for generating long haul truck flows. These trucks use 70 directional links to carry goods to and from the HRM. The port of Halifax is located in the heart of its urban core, which includes the downtown areas of Halifax and Dartmouth. Two container terminals and one intermodal terminal owned by Halifax Port Authority are also located in the urban core. Connecting Halifax and Dartmouth are two suspension Bridges: the Angus L. Macdonald and the A. Murray Mackay Bridge. These bridges are coded in the network model where only the Mackay Bridge allows trucks and offers a direct connection to the port. A representation of Halifax transport network model within EMME is presented in Figure 2-4.

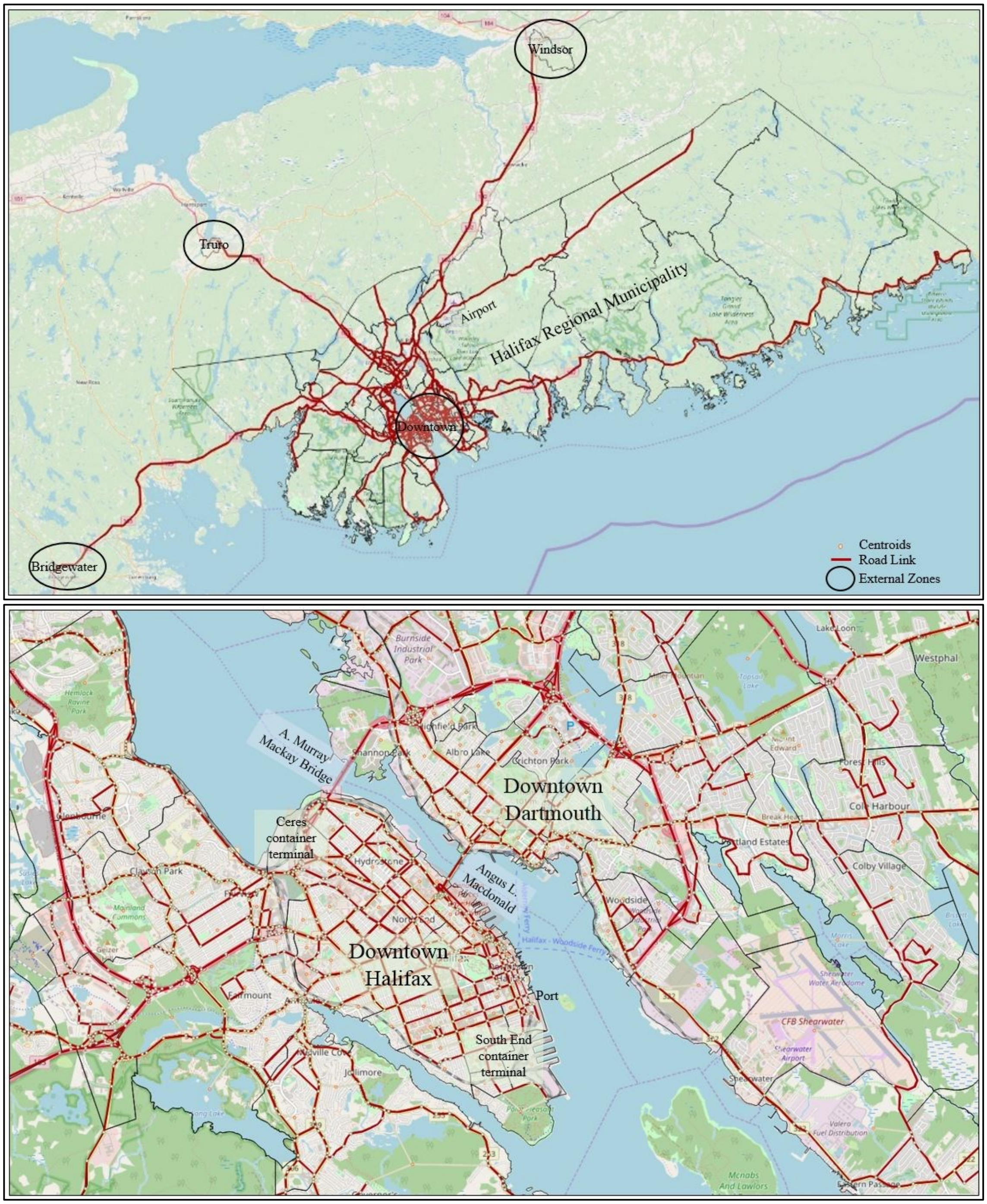


Figure 2-4 Halifax Regional Transport Network Model Coded Within EMME/4 Platform (a) Full HRM (b) Downtown Core

2.3.3.1 *Coordinate System and Projection*

Halifax transport network model used the Modified Transverse Mercator (MTM) Coordinate System. This system uses Transverse Mercator Projection with zones spaced 3° of longitude apart. Central meridian is located at 64° 30" W and scale factor at central meridian is 0.9999. The original version of MTM is used in this study, which is also known as ATS 1977 MTM 5 (version 0). To enable interchanging EMME and GIS files, the full extent of MTM should be compatible with all network X-Y co-ordinates.

2.3.3.2 *Nodes and Links*

The process of translating the transport network system into a computer usable format is known as network coding. The basic elements of a road network file are nodes and links. Nodes represent the intersection of roadway segments and are also used as shape points to maintain the true topology of the roads highways system. Link is a connecting line between two nodes and represents part of a road segment. Links are constructed to represent five classes of roads within HRM which includes highways, arterial roads, collector roads, bridges and trunk highways and ramps. The network model includes 2449 nodes.

Table 2-2 List of Nodes within the Transport Network Model

Area	Number of Zonal Centroids	Number of Total Nodes	Number of Nodes in a TAZ		
			Minimum	Average	Maximum
Urban Core	92	614	1	6.7	27
Suburban Area	95	1412	1	14.9	83
Rural Area	32	391	1	12.2	38
External	3	32	1	10.7	13

In total 5272 links are coded to represent individual roadway segments. Almost all roads in Halifax allow passenger cars with restrictions for truck traffic. Some road segments prohibit trucks, others have restriction for night time use only (from 9pm to 7am). Only a few major connector roads allow truck traffic 24 hours per day. This network allows 3548 truck-permitted links so that any prohibited routes are not available for truck trips. In addition, there is information about the number and direction of lanes in each link, length of each links, design capacity, design speed, permitted modes over the link, and other external attributes such as link surcharge. Right hand rule is followed for vehicle movement.

Table 2-3 Details of Link Functional Class and Volume Delay Function Indices within the Transport Network Model

Road Type	Area	Number of Links	Link Length (m)				VDF Used
			Minimum	Average	Maximum	Total	
Highways	Urban Core	135	31.2	196.0	1015.5	26465.0	1
	Suburban Area	511	15.1	328.4	5902.5	167815.2	
	Rural Area	165	44.4	1201.0	11748.4	198169.5	
	External	45	314.7	5996.4	13732.2	269835.7	
Ramp and Trunk Highways	Urban Core	495	13.0	179.0	919.6	88591.8	2
	Suburban Area	1234	12.6	238.8	3411.4	294675.3	
	Rural Area	375	47.0	1611.3	16046.4	604254.8	
	External	0	0	0	0	0	
Major Country Roads	Urban Core	351	12.6	241.0	996.8	84604.0	3
	Suburban Area	755	21.3	304.9	2802.0	230182.9	
	Rural Area	160	39.7	591.5	2364.8	94634.1	
	External	0	0	0	0	0	
Other Arterials	Urban Core	207	17.6	213.6	626.3	44221.5	4
	Suburban Area	171	28.6	376.6	2452.0	64396.6	
	Rural Area	28	288.2	2162.7	6925.2	60554.8	
	External	0	0	0	0	0	
Collector Roads	Urban Core	220	16.2	229.0	620.6	50373.2	5
	Suburban Area	304	22.4	495.7	3944.0	150685.6	
	Rural Area	74	387.5	2864.7	11781.7	211987.2	
	External	6	1541.4	2464.3	4142.8	14785.9	

Traffic congestion is accounted using five volume delay functions (VDF) that represent five different classes of roads constructed for Halifax transport network model. The VDF functions are enclosed in Appendix A and Table 2-3 shows the detailed link functional class and volume delay function indices at different areas of the transport network model.

2.3.3.3 *Zonal Centroids*

There is another special type of nodes within the model called centroids. Centroids represent the traffic analysis zones (TAZ) and are located approximately at the population or employment center rather than the geographic center of that TAZ. So, the number of zonal centroids is equal to the total number of TAZ, which is 222, within our transport network model. They are the point at which trips are loaded or terminated into the network.

2.3.3.4 *Zone Centroid Connector*

Link that connect a zonal centroid with the local road in the network is called a zone centroid connector. There could be more than one connector from a centroid. Maximum length and number of connectors may vary zone to zone. For Halifax transport network model, maximum number of connectors per zone is 4 and length of connector varies from 0.016 km (located in urban core) to 11.78 km (located in rural area).

Table 2-4 Details of Zone Centroid Connector Links within the Transport Network Model

Area	Number of Connectors	Average Connector per TAZ	Connector Link Length (m)			
			Minimum	Average	Maximum	Total
Urban Core	220	2.4	16.2	229.0	620.6	50373.2
Suburban Area	304	3.2	22.4	495.7	3944.0	150685.6
Rural Area	74	2.3	387.5	2864.7	11781.7	211987.2
External	6	2.0	1541.4	2464.3	4142.8	14785.9

2.3.3.5 *Turns*

EMME enables modellers to control turning of vehicles at intersection in appropriate direction using the command 'Turn'. Turn confirms relevant turning movement of vehicles and restrict unrealistic traffic movement (for example, vehicle movement from one ramp to another ramp). Figure 2-5 shows that how ramp to ramp traffic movement can be restricted by using turn. Such turn are placed where necessary, in total 507 turns are used in 137 intersections within the transport network model.

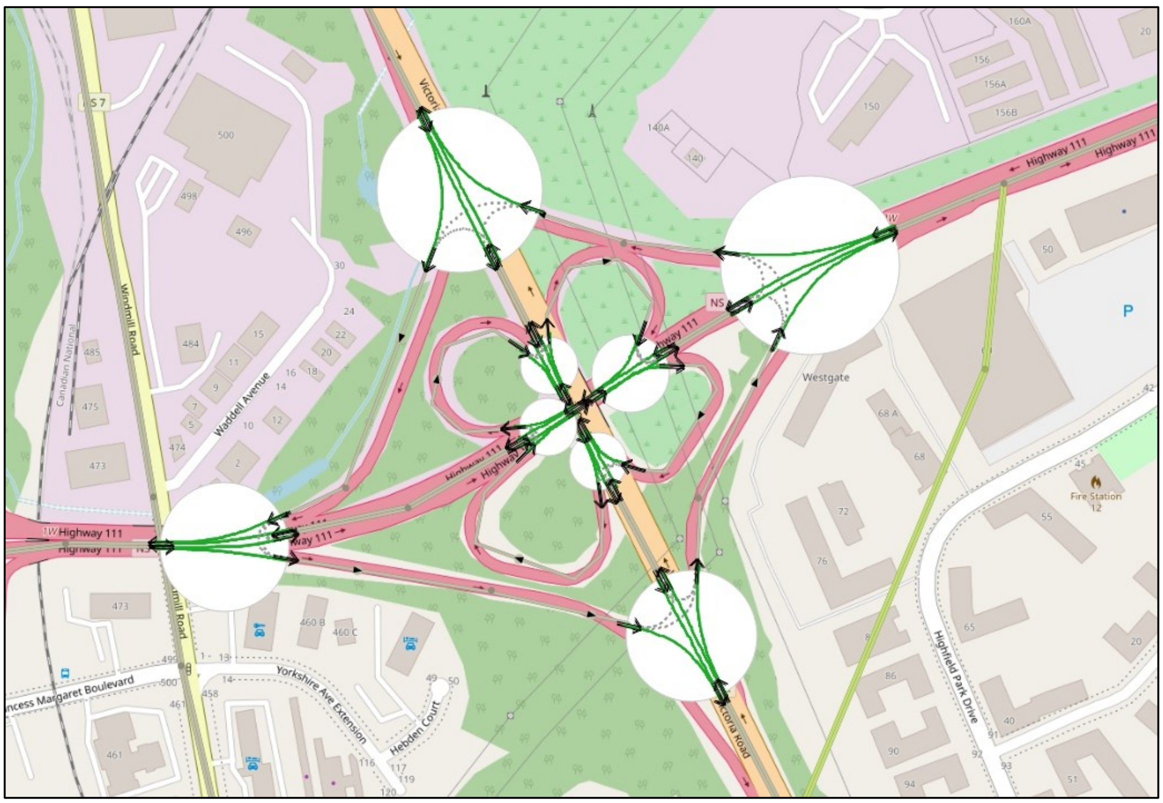
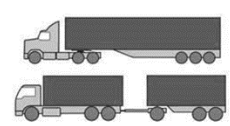


Figure 2-5 Network Connection after Using Turns in Intersections

2.3.3.6 *Modes*

Modes are designated within EMME using a single-letter case-sensitive code that indicates different vehicle type. Each link in the network permits at least one mode. The codes corresponding to permitted modes are included into the attribute list of each link. In total six modes are allowed within the network. Each mode is assigned within four generic mode types (i.e. Auto, Transit, Auxiliary Auto, and Auxiliary Transit) supported by EMME. A detailed list of modes is presented in Table 2-5.

Table 2-5 List of Available Modes within the Transport Network Model

Mode	Description	Type declared in EMME	Modes considered in this study	Example
a	Passenger Car (four tires, two axles)	Auto	Yes	
b	Metro Transit	Transit	No	
c	Walk	Auxiliary Transit	No	
d	Light Truck (four or more tires, two axles)	Auxiliary Auto	Yes	
e	Medium Truck (six or more tires, two to four axles)	Auxiliary Auto	Yes	
f	Heavy Truck (double or triple unit, combinations, five or more axles)	Auxiliary Auto	Yes	

2.3.3.7 *Additional Link Attributes*

Generally, EMME outputs the total traffic volume per link. To achieve classified traffic volume information for each link, external attribute needs to be created using the Modeller tool of EMME. Such four extra attributes have been created to store the link volume for each of four modes. Which helps to show link volumes of different modes separately. Moreover, for calibration and validation purpose, a cost attribute is usually imposed to links to regulate the traffic volume encountered by them in order to minimize the deviation between the observed and simulated traffic flows. Four cost attributes are created to control the flow of four modes separately.

2.3.4 Passenger Car Demand Forecasting Model

Several guidelines on the development of travel demand forecasting procedures are well documented in literature *(Ortuzar and Willumsen, 2011; Mayer and Miller, 2001; Hutchinson, 1974; Kanafani, 1983; NCHRP report 716).* This modeling system predicts the number of trips produced from or attracted to a TAZ, specific modes used to make those trips, time of the day of the trips, origin-destination (O-D) trip flows and finally routes taken to complete the trips from one TAZ to another within the transport network model. The steps of traditional four stage travel demand forecasting modeling (i.e., Trip Generation, Trip Distribution, Mode Split and Traffic Assignment) are shown in Figure 2-6 *(Mayer and Miller, 2001).*

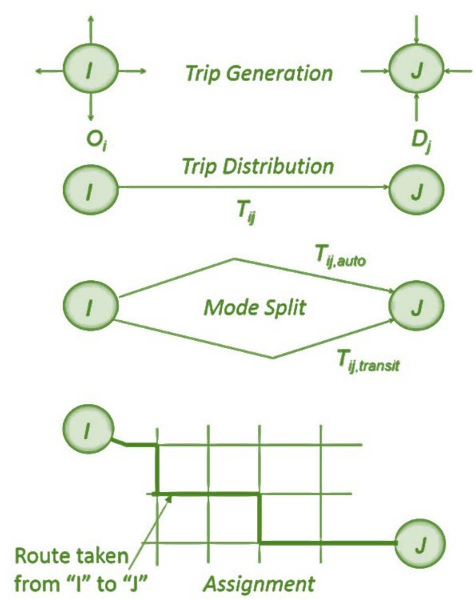


Figure 2-6 Steps of Four Stage Travel Demand Modelling

In this chapter, the travel demand forecasting model is referred to the year of 2011. This study utilizes a regression model, a Gravity Model and a Multinomial Logit Model developed by Dalhousie Transportation Collaboratory (DalTRAC) to obtain the total trips generation and distribution by modes in the network *(Rahman and Habib, 2015).* However, an extensive calibration and validation is performed during the traffic assignment phase to minimize the absolute deviation between the observed and simulated traffic volumes in the network. A 'Link surcharge' technique is also applied to regulate the link traffic flows and improve the replication of the actual traffic condition within the model. This study models five types of trips which include Home based Work (HBW) trips, Home based School (HBS), Home based Shopping (HBSh), Home based Other (HBO) trips and Non-Home based (NHB) trips. In mode choice modeling, four different modes are considered which include passenger car, transit, bike and walk. Then, trip tables, alternatively preferred as O-D matrices are constructed which provide information on the trip flows by time of the day and by modes among TAZs followed by the traffic assignment in the network. This chapter describes the detailed procedure of the development of the four-stage travel demand model.

2.3.4.1 *Data Used*

Travel demand forecasting modeling requires the use of different socio-demographic characteristics data such as zonal population, household characteristics, employment rate, and income. Multiple data sources including National Household Survey (NHS) 2011, Census Tract (CT) 2011, and Enhanced Points of Interest (EPOI) data obtained from Desktop Mapping and Technological Inc. (DMTI) Spatial are utilized for modeling of the trip production and attraction. Other data source, for example, Household Mobility and Travel Survey (HMTS) which was conducted in Halifax, Nova Scotia in 2012-2013 is used for mode choice modeling. Time of the day of the trips information is extracted from the General Social Survey (GSS) data 2009. This survey data can provide the information on different trip purposes, for example, work, school, shopping, grocery etc. This also informs the start time of the trips of different purposes.

2.3.4.2 *Trip Generation*

In the first phase of four stage travel demand modeling, the total number of trips produced from and attracted to each TAZ is estimated. Trip production at a certain TAZ depends on its socio-demographic, and land use diversity. The variables that affect trip production include employment, household size, income and neighborhood characteristic for example, a sub urban area generates higher trips in the morning. National Household Survey (NHS) 2011 provides population, and household size, employment and income and number of work trips data at 87 Census Tract (CT) level in Halifax. This information is transferred to the 'TAZ' level, a geographic unit used in this study. A detailed procedure of transferring the data from CT level to TAZ level can be found in section 3.3.1.2. There are several methods of estimating trips produced from a TAZ which includes cross-classification, regression and trip rate analysis *(Ortuzar and Willumsen, 2011; Mayer and Miller, 2001; Hutchinson, 1974; Kanafani, 1983).*

The estimation of trips production for regional transport network model of 2011 is based on a regression analysis model in this chapter. The result of regression analysis model is enclosed in Appendix B (Table B-1 and Table B-2). However, after the Nova Scotia Travel Activity (NovaTRAC) Survey 2016 data becomes available, a trip rate analysis method is used to estimate the trips generation for the model of 2016 (see next chapter). Generally, a regression analysis is founded on a linear relationship where trips produced from a TAZ are a function of the socio demographic and land use characteristics of that zone. Assume, l is the number of trips produced in a TAZ, z and $v_1, v_2, v_3, \ldots\ldots\ldots\ldots\ldots v_n$ represent the socio demographic and land use characteristics of z, then the relationship between l_i and v_i can be expressed as follows:

$$l_i = \lambda + \sum_{i=1}^{n} \beta_i * v_i \quad \text{...(1)}$$

λ is a constant and β depends on the specific attributes of z contributing to the trips production in this area.

On the other hand, trip attraction can be calculated from the Enhanced Point of Interest (EPOI) data assuming that the trip attraction is proportional to the growth potential of different establishments such commercial, industrial, service sector, educational institute, and hospitals.

2.3.4.3 *Trip Distribution*

The task of this stage is to link up the TAZ trip ends predicted by the trip generation phase to forecast trip flows, T_{od}^{r} from each production TAZ, o to each attraction TAZ, d. There are several methods including growth factor, and gravity model to conduct trip distribution. Gravity model is most widely used and is considered in this chapter. This phase outputs origin- destination trip flow matrices which display the number of trips going from each origin to each destination, where o represents rows (origins) and d stands for columns (destinations). According to Gravity Model *(Mayer and Miller, 2001)*, trip flows can be estimated using the following expression:

$$T_{od}^{r} = \frac{P_o \left[A_d f_{od} k_{od} \right]}{\sum_{n=1}^{s} A_d f_{od} k_{od}} \quad \text{...(2)}$$

Where, P_o = Total number of trips produced in TAZ o

A_d = Total number of trips attracted to TAZ d

f_{od} = Friction factor, which is the inverse of the 'cost' of the travel between o and d

k_{od} = Socio-economic factor for trip interchanges between o and d

T^r_{od} = Total number of trips produced at TAZ o and attracted to TAZ d

The constraint that the total number of trips anticipated to leave any TAZ o is equal to the observed productions, P_o is automatically satisfied within the equation. But it does not necessarily satisfy the converse constraint that the total number of trips predicted to enter TAZ d is equal to the observed attractions A_d. Attractions are adjusted through an iterative process until both the predicted and observed values are equal or the deviation in between is within a tolerable limit. The value of k is determined based on existing practice and found as 1.0 from several available technical reports *(NCHRP report 716; IBI group, 2009a; IBI group, 2009b).* At the end of the trip distribution stage, an O-D matrix containing total trips from each to all TAZs for 24-hour period is obtained. To obtain the hourly O-D matrix from 24-hour period O-D matrix, time of the day information of the trips is utilized which is obtained from the General Social Survey (GSS) data of 2009.

2.3.4.4 *Mode Split*

This phase models the traveler's mode choices for making their trips of different purposes. Modal split information is critical to split the 24-hour period O-D matrix by modes which feed the multiclass traffic assignment within the transport network modeling platform. This study uses a mode choice model that was developed following a discrete choice modeling technique more specifically, a 'Multinomial Logit Modeling (MNL)'. The results of MNL model is enclosed in Appendix C (Table C-1). This technique involves maximization of a log likelihood function, which can be computed using different econometric modeling tools such as NLOGIT. Mode choice modeling considered auto driver, auto passenger, transit, bike and walk. Since, transit component of the model is not utilized in this model, the MNL model was used for the determination of passenger car O-D alone. In this chapter, auto driver means the trip maker driving by own and auto passenger means trip maker travelling as a passenger while using passenger car as a selected mode. The share of the different modes in Halifax is illustrated in Figure 2-7.

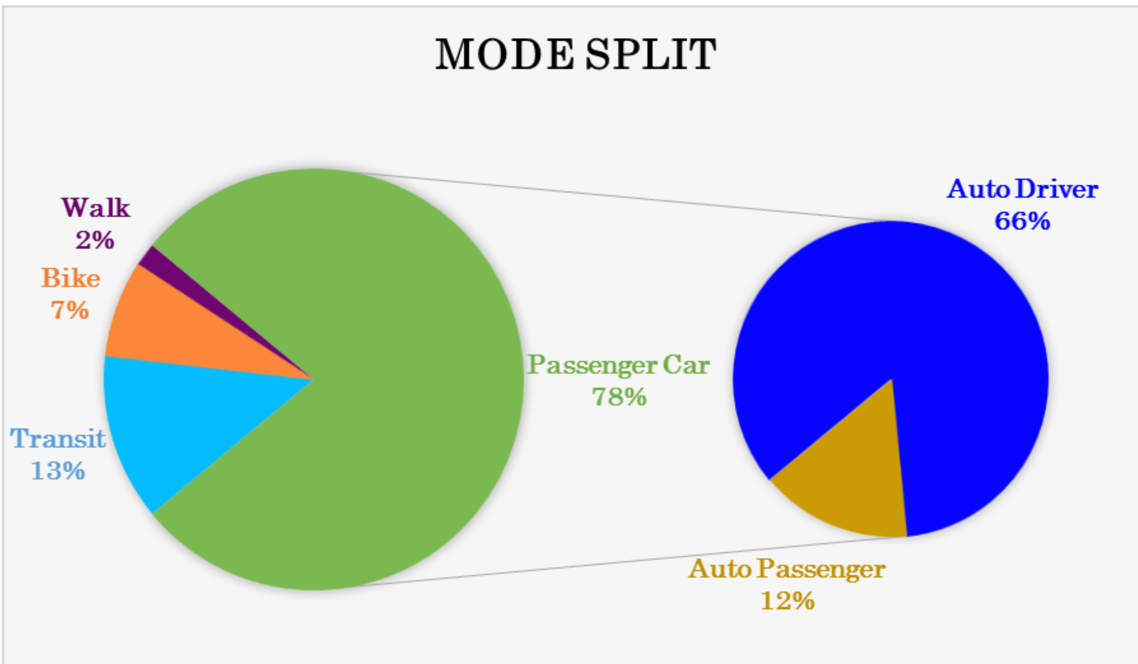


Figure 2-7 Mode Split for the Year of 2011

As the results suggest that the major portion of the trips are made by passenger car which is 78%, this study assumes the effect of other modes in congestion will be minimal. Therefore, movement of passenger car in combination with commercial vehicles is assigned within the multiclass traffic assignment platform.

2.3.5 Commercial Vehicles Demand Forecasting Model

The development of travel demand forecasting model for commercial vehicles is almost similar to that for passenger car; only exception is, mode choice modelling step is eliminated from the four-stage travel demand forecasting model. The reason can be argued as, this study utilized a Quick Response method which involves estimating the O-D trip table directly using trip generation rates and trip distribution models at the TAZ level. Using different trip rates for different truck types automatically eliminates the mode split step *(Beagan et al., 2007).* Moreover, this study assumes no other potential modes (such as ferry, train or air cargo) carrying freight within the transport network. Only the goods carried by trucks are modelled in this study. Three truck types considered for this study includes: light truck, medium truck and heavy truck. Detailed procedure of three-stage commercial vehicle demand forecasting modelling for Halifax is described in this section.

2.3.5.1 *Data Used*

Collecting data for the Development of commercial vehicles travel demand model is expensive, and time consuming. Necessary data for truck trip generation and movement is limited. This study extensively uses SHAW GPS tracking data, trip rates for different truck types and Enhanced Points of Interest (EPOI) data obtained from 'Desktop Mapping and Technological Inc. (DMTI) Spatial' to estimate truck trip generation and their location. SHAW GPS data provides the information about external-internal and internal-external movement of heavy trucks. EPOI data informs the location, and number of commercial establishments within HRM. Passenger car equivalent (PCE) values for different truck types are obtained from the guidelines of Quick Response Freight Manual *(Beagan et al., 2007).*

2.3.5.2 *Trip Generation*

The Enhanced Point of Interest (EPOI) data obtained from DMTI Spatial was used to generate production and attraction of light, medium and heavy truck trips. EPOI data informs the location, industry classification (NAICS) and number of commercial establishments within HRM. There are in total 33,946 establishments within fourteen types of establishments. All establishments are re-grouped into four broad categories: Agriculture, Construction, Mining, MTCUW (Manufacturing, Transportation, Communications, Utilities and Wholesale), Retail Trade, Office and Services (Table 2-6) according to their NAICS code as they generate a major portion of truck trips *(Beagan et al., 2007; IBI Group 2009a)*. A pivot table is used to summarize number of establishments for all categories. Trip generation is estimated by multiplying these values with corresponding trip rates obtained from a study of commercial vehicle for the region of Peel for all truck types *(IBI Group 2009a)*. All establishments are geocoded using their longitude and latitude values within the developed Halifax Transport Network Model. Once all establishments are identified for each TAZs, the total number of trips generated from each TAZ is estimated.

Table 2-6 Classification of Four Establishments Categories

Establishment Types	Elements (parenthesis numbers indicate 2-digit NAICS code)
Agriculture, Construction, Mining	Agriculture, Forestry, Fishing and Hunting (11) Mining and Oil and Gas Extraction (21) Construction (23)
MTCUW (Manufacturing, Transportation, Communications, Utilities and Wholesale)	Manufacturing (31 to 33) Transportation and Warehousing (48, 49) Accommodation and Food Services (72) Utilities (22) Wholesale Trade (41)
Retail Trade	Retail Trade (44,45)
Office and Services	Administrative and Support, Waste Management and Remediation Services (56)

A study shows that light vehicles are used for time-sensitive and local movements and larger and heavier vehicles for long haul movements *(Cavalcante and Roorda, 2010).* Long haul truck trips are the internal-external and/or external-internal movements of heavy trucks, which originated from or are destined to HRM. Long haul truck movement information is extracted from SHAW GPS tracking information data *(Kevin et al., 2016).* This GPS dataset has a record of approximately 56,000 Canadian-owned trucks and Halifax-related data was clipped from the original database. The number of truck trips originated from and destined to each internal TAZ are estimated from the clipped data. To determine the trips within the GPS dataset, stop events are observed for the trucks based on 15 minutes intervals or longer. The stop events were classified as primary (where goods are likely transferred) or secondary (where the truck stops for fuel refills, driver breaks, etc.). Finally, the trips are identified based on the primary stop events as start/end points along with a time constraint to ensure that the trip is reasonable based on the distance travelled. Each data record has information about the time and location of a truck, with an identification number. Raw GPS data records are then converted into truck trips and all information was kept anonymous to protect the identities of trucks. The data covers the production and attraction values for one month in March 2016 with total 31days (23 day during the work week, and 8 days on the weekend). The full methodology of converting GPS data into truck trips is outlined in a study of Kevin et al. *(2016).*

Adjustments of Special Generators

Ports, two container terminals and the intermodal terminal act as special generators for commercial vehicle movements over Halifax. A study conducted by Marinova Consulting Ltd. reported the average number of daily standard containers carried out between the intermodal terminal and ports *(MariNova Consulting Ltd., 2006).* The Cargo Statistics of Halifax Port Authority (HPA) reveals the volume of cargo handled by the port of Halifax in the year of 2011. The volume of cargo is converted into number of trucks using a guideline from quick response freight manual *(Beagan et al., 2007)*. These truck trips are distributed within these container terminals according to their cargo throughput capacity. Truck trips produced from and/or destined to special generator are added to previously calculated trip generation values of the corresponding TAZs.

2.3.5.3 *Trip Distribution*

Once total production and attraction values for each truck type are estimated, these are separated into three periods (morning, mid-day, evening) according to the share of total truck trips during these periods obtained from the HRM traffic count data. It was observed that 48% of truck trips occur in mid-day, whereas 19% and 33% truck trips occur during morning and evening peak times respectively. Once the production and attraction values for each truck type are obtained, an O-D matrix for each type of truck is prepared utilizing a gravity model. This is the same procedure that is described for trip distribution of passenger car in section 2.3.4.3

2.3.6 Preparation of O-D Matrices

At this stage, when trip generation, distribution and modal split components produce outputs with time of the day information, zonal trip flows at an hourly interval and by mode are obtained. Each model is executed for all 222 TAZs and thereby all O-D matrices prepared in this study are of the dimension of 222x222. In total twenty-four separate O-D matrices are prepared to represent the hourly passenger car trips generated for a day. A representation of hourly passenger car flow pattern is shown in Figure 2-8.

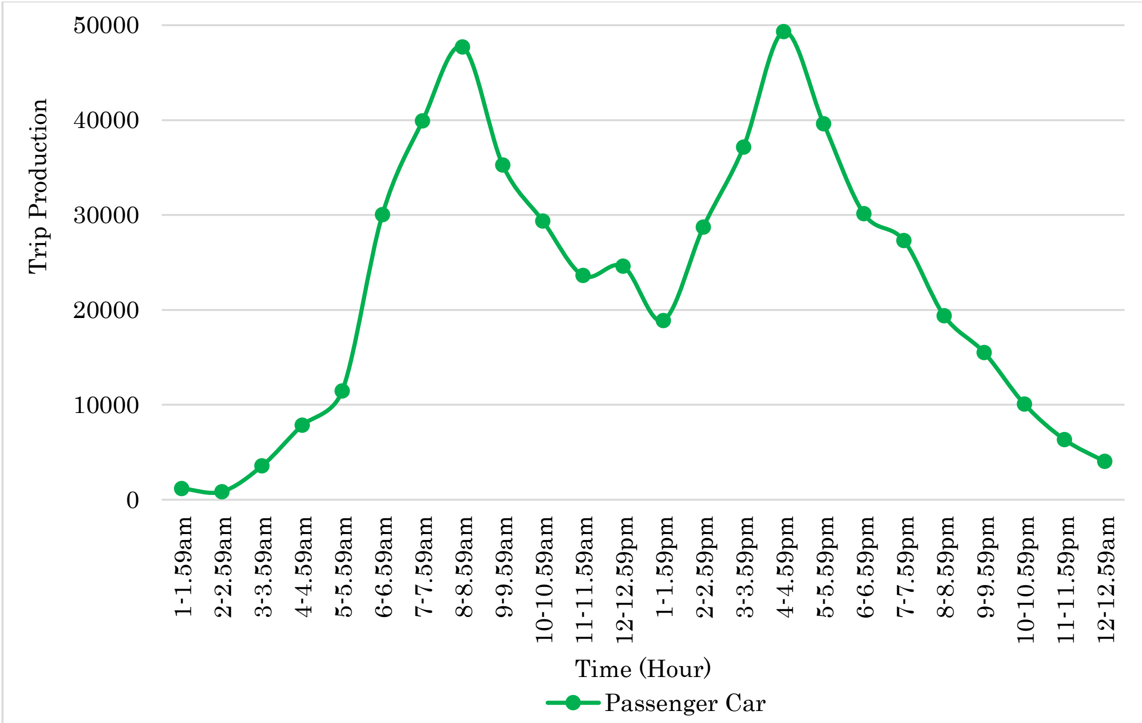


Figure 2-8 Hourly Passenger Car Flow Pattern

Truck flows are considered for morning peak (7:00am to 8:59am), Mid-day peak (11:00am to 12:59pm), and evening peak (4:00pm to 5:59pm) period. Six O-D matrices are prepared for each truck types to represent the hourly truck trips. O-D matrices of trucks are converted into "Passenger Car Equivalent" matrices before conducting the multiclass traffic assignment. To do so, Passenger Car Equivalent (PCE) 1.5, 2.0 and 2.5 are used for light, medium and heavy trucks as per QRFM Guideline *(Beagan et al., 2007; IBI, 2009b)*. A representation of hourly truck flow pattern is shown in Figure 2-9. After this process, all forty-two (twenty four for passenger car and eighteen for three different truck types) O-D matrices are converted into a computer readable format. The O-D matrices obtained at this stage are known as 'Seed O-D Matrices' which will be modified through calibration and validation procedures. The calibration and validation process start with the traffic assignment.

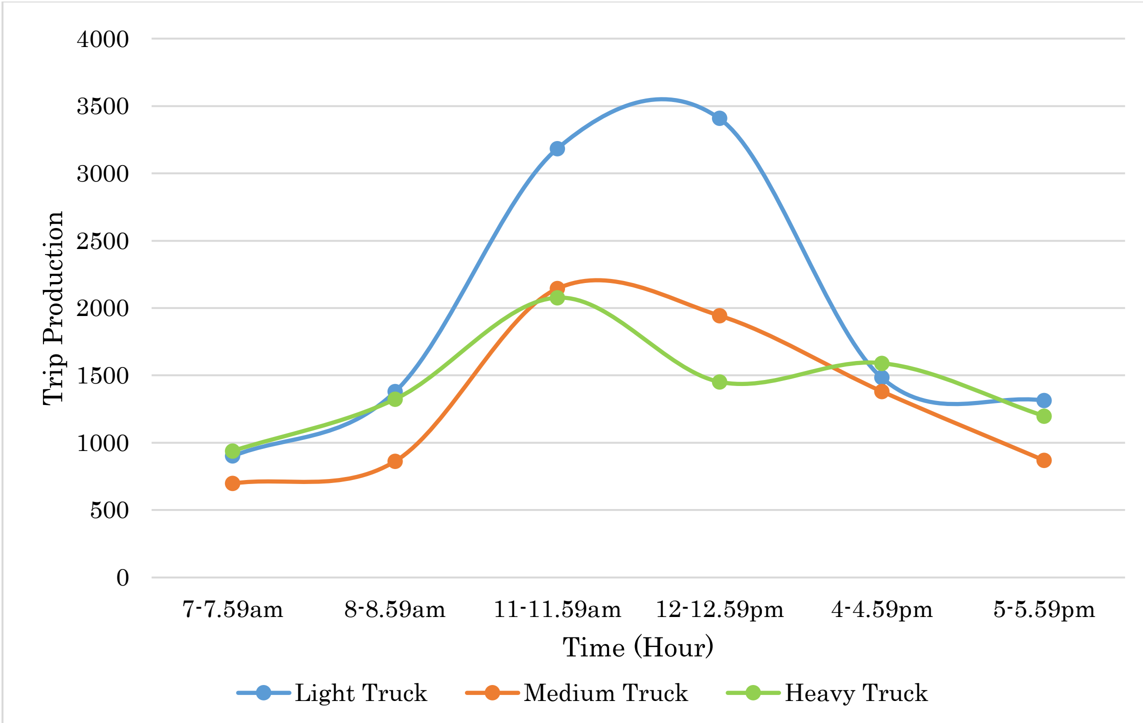


Figure 2-9 Hourly Truck Flow Pattern

2.3.7 Multiclass Traffic Assignment

Once the O-D matrices for passenger cars and trucks are prepared, a multiclass traffic assignment is performed using a user equilibrium assignment principle within the developed transport network model. A standard method is used to solve the user equilibrium multiclass traffic assignment principle. This principle aims to minimize the overall travel time along the congested road links. The congested link discourages more travelers from using it given that there exist alternative options. Thus, this technique iteratively solves for the link flow and cost to establish a user-equilibrium conditions in the network. Figure 2-10 shows a simplified sample of vehicle movement in a standard multiclass traffic assignment with different volume delay function for different road types where sequence of link congestion level is VDF3> VDF2> VDF1.

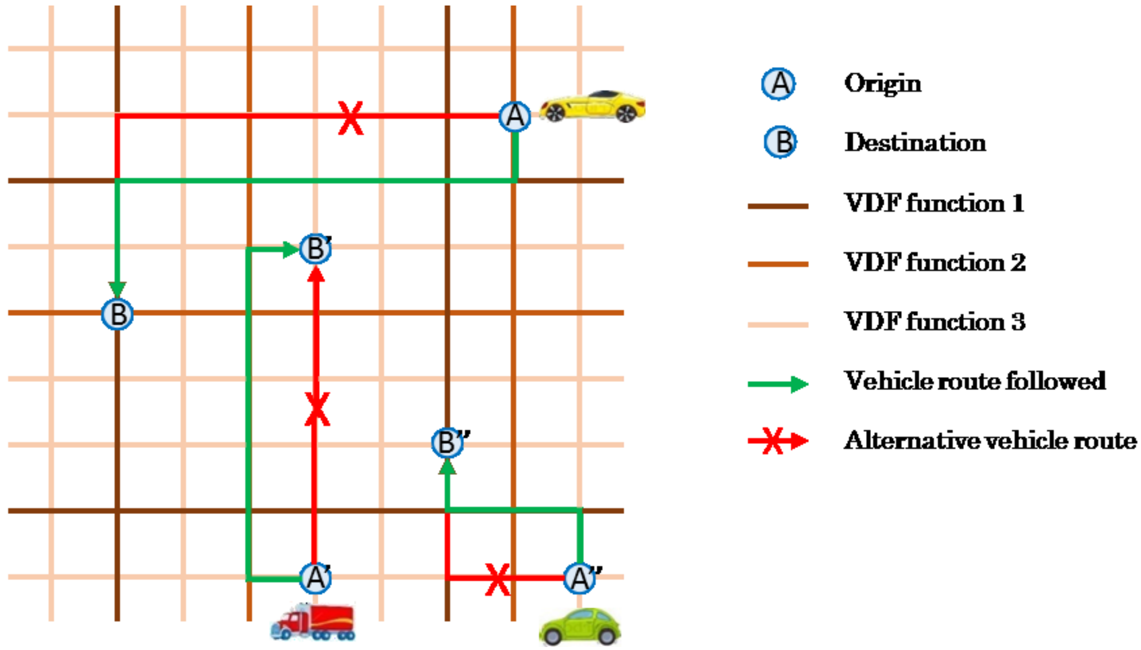


Figure 2-10 Sample Vehicle Movement in a Standard Multiclass Traffic Assignment

2.3.7.1 *Mathematical Formulation*

In the case of multiclass user equilibrium assignment problem, the perceived cost by each class of vehicles on a link is different. Let's assume, a set of vehicle class is defined as C_V, and a set of network links is L, where $C_V = \left\{ c^{Passenger\ Car}, c^{Light\ Truck}, c^{Medium\ Truck}, c^{Heavy\ Truck} ....c^i \right\}$ and $L = \left\{ l^1, l^2, l^3, ... l^n \right\}$. If c^i represents a vehicle class and l^n represents a candidate link, where $c^i \in C_V$ and $l^n \in L$, then the cost for vehicle class, c^i is a function of the volume of that class, v_l^{ci} on the link l^n. Then mathematically, the cost could be defined as $s_l^{ci}(v_l^{ci} / c^i \in C_V)$.

Multiclass traffic assignment assumes that all the different classes, c^i are subjected to the same congestion effect resulted from the total volume of the link; however, each traffic class perceives a different constant bias b_l^c. The cost of link l^n perceived by a traffic class, c^i can then be defined according to Noriega and Florian *(2007)* as follows:

$$s_l^{ci}\left(v_l^{c^i}\right) = s_l\left(v_l^{c^i}\right) + b_l^c \quad \text{.....(3)}$$

This study implements multiclass traffic assignment model in EMME and computes the equilibrium flows and travel times by solving the following problem:

$$\text{Min } f(v) = \sum_{l \in L} \int_0^{v_l} s_l(v + \overline{v_l})dv + \sum_{l \in L}\sum_{c \in C} b_l^c v_l^c + \sum_{j \in J}\sum_{l_1 \in L_j^-}\sum_{l_2 \in L_j^+} \int_0^{v_{l_1 l_2}} o_{l_1 l_2}(v + \overline{v_{l_1 l_2}})dv \quad \text{.....(4)}$$

Subjected to,

$$v_l = \sum_{k \in K} \delta_{lk} h_k \qquad l \in L \quad \text{.....(5)}$$

$$v_{l_1 l_2} = \sum_{k \in K} \delta_{l_1 l_2 k} h_k \qquad l_1 \in L_j^-, l_2 \in L_j^+, j \in J \quad \text{.....(6)}$$

$$\sum_{k \in K_{od}^c} h_k = g_{od}^c \qquad o \in O, d \in D, c \in C \quad \text{.....(7)}$$

$$h_k \geq 0 \qquad k \in K_{od}^c, o \in O, d \in D, c \in C \quad \text{.....(8)}$$

2.3.7.2 *Convergence Measures*

As the objective function is convex, implementation of multiclass traffic assignment in EMME utilizes a second-order linear approximation method to determine the solution of the sub problem that provides a lower bound (LB), for the optimal value of the objective function $f(v^*)$:

$$LB = f(v) + \sum_{l \in L} s_l(v_l + \overline{v_l})(y_l - v_l) + \sum_{l \in L}\sum_{c \in C} b_l^c (y_l^c - v_l^c) + \sum_{j \in J}\sum_{l_1 \in L_j^-}\sum_{l_2 \in L_j^+} \int_0^{v_{l_1 l_2}} o_{l_1 l_2}(v_{l_1 l_2} + \overline{v_{l_1 l_2}})(y_{l_1 l_2} - v_{l_1 l_2})$$

....(9)

Where, $f(v)$ is the current value of the objective function.

The largest value of LB obtained up to the current iteration is referred to the current best lower bound (BLB). Then, one of the criteria named as 'best relative gap' to measure the closeness between the performed assignment and the perfect assignment can be expressed as follows:

$$Best\ Relative\ Gap\ =\ \left(f\left(v\right)\ -\ BLB\right))\ /\ f\left(v\right)\ *\ 100 \text{ ....(10)}$$

The solution of the sub problem offers another criterion named as 'absolute gap' which further estimates two criteria (i) relative gap, and (ii) normalized gap to compare the assignment with the perfect assignment. The relative and normalized gap can be computed as follows:

$$Relative\ Gap\ =\ Absolute\ Gap\ /\ \left(\Sigma\ volume\ *\ cost\right) \text{ ....(11)}$$

$$Normalized\ Gap\ =\ Absolute\ Gap\ /\ \Sigma_c \Sigma\ demand\ assigned_c \text{ ....(12)}$$

2.3.7.3 *Advantages of Using Multiclass Traffic Assignment*

The advantage of using multiclass traffic assignment is that it incorporates multiple modes within a single traffic assignment so the combined traffic congestion in the network is captured. Thus, a simulation model can replicate the actual traffic conditions of the road network. In this assignment process, truck trips are assigned together with the passenger car model, because congestion has a significant impact on travel times experienced by trucks. In this assignment process, the input matrices for different vehicle classes (i.e., passenger cars, light, medium and heavy trucks) are assigned altogether. For this study, hourly separate multiclass traffic assignment is performed for twenty-four hour period among them trucks are considered for three peak periods (morning peak from 7:00am to 8:59am, Mid-day peak from 11:00am to 12:59pm, and evening peak from 4:00pm to 5:59pm period). A sample of multiclass traffic assignment performance is shown in Appendix D. Number of vehicles present within the network and number of iterations required to complete each hour of assignment is listed in Table 2-7. Table results show that higher number of vehicles is present in the network during morning (from 7:00pm to 8:59pm) and evening peak periods (from 4:00pm to 4:59pm). Consequently, the traffic assignment models for these periods require higher number of iterations to establish the equilibrium traffic condition satisfying the converging criteria considered in this study.

Table 2-7 Number of Iterations Required in Trip-based Multiclass Traffic Assignment

Time period	Iteration required	Number of Vehicles in the Network
12:00-12:59am	2	129,957
1:00-1:59am	2	43,376
2:00-2:59am	2	34,235
3:00-3:59am	2	113,535
4:00-4:59am	2	252,443
5:00-5:59am	2	387,007
6:00-6:59am	3	1,032,272
7:00-7:59am	5	1,521,493
8:00-8:59am	5	1,832,215
9:00-9:59am	3	1,284,062
10:00-10:59am	2	1,012,654
11:00-11:59am	2	1,073,754

Time period	Iteration required	Number of Vehicles in the Network
12:00-12:59pm	2	1,117,297
1:00-1:59pm	2	648,771
2:00-2:59pm	2	992,769
3:00-3:59pm	3	1,346,384
4:00-4:59pm	5	1,997,006
5:00-5:59pm	4	1,571,654
6:00-6:59pm	2	1,035,363
7:00-7:59pm	2	946,210
8:00-8:59pm	2	663,218
9:00-9:59pm	2	536,871
10:00-10:59pm	2	330,716
11:00-11:59pm	2	200,677

2.3.8 Calibration and Validation of the Model

A traffic volume-based approach is adopted for an extensive calibration and validation of the traffic flow in the simulation model. The simulated and observed traffic count is compared and the deviation is evaluated in terms of R2, RMSE (Root Mean Square Error), and GEH (Geoffrey E. Havers, Statistics) values. The traffic routing calibration is performed following a link surcharge method in which an extra attribute of cost is created to attract or distract traffic depending on the anticipated volume. The cost is assigned to links through an iterative process until the deviation between observed and simulated truck count is minimized. In total, nine key locations of urban core (Figure 2-11) are validated with six hours (two hours of each morning, mid-day and evening peak period) of observed field traffic count data.

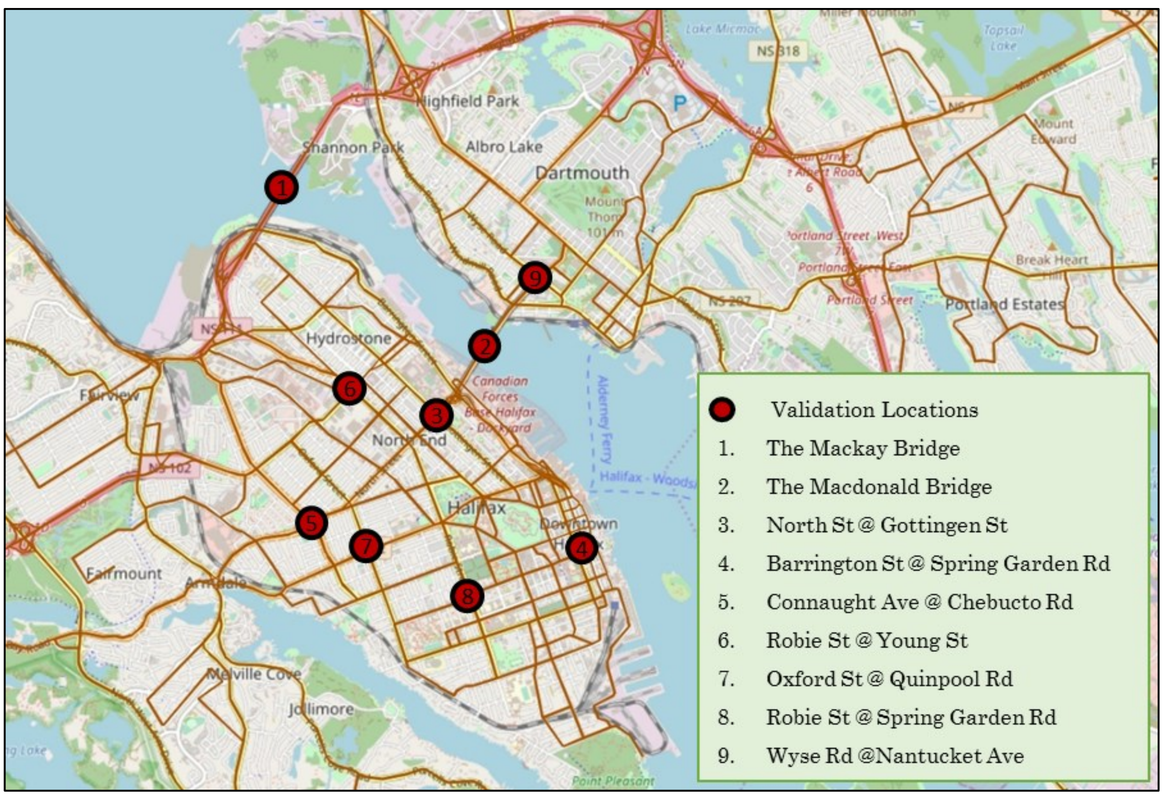


Figure 2-11 Validation Location for the Study

Equations to measure RMSE and GEH are shown below.

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(S^i - O^i)^2} \quad \text{.......}(13)$$

$$GEH = \sqrt{\frac{2*(S-O)^2}{S+O}} \quad \text{.......}(14)$$

Here, S = simulated traffic count from the model, O = observed field traffic count and N = number of data set.

The validation results are shown in Table 2-8.

Table 2-8 Validation Results for Trip-based Model

Criteria	Time	Value	
R^2	Morning Peak (7:00-8:59am)	0.93	
	Mid-day Peak (11:00am-12:59pm)	0.84	
	Evening Peak (4:00-5:59pm)	0.83	
RMSE	Morning Peak (7:00-8:59am)	259.8	
	Mid-day Peak (11:00am-12:59pm)	238.9	
	Evening Peak (4:00-5:59pm)	360.2	
GEH	Morning Peak (7:00-8:59am)	GEH < 1	50.0%
		1 < GEH < 2	17.6%
		2 < GEH < 5	20.3%
		5 < GEH < 10	12.2%
	Mid-day Peak (11:00am-12:59pm)	GEH < 1	44.6%
		1 < GEH < 2	21.6%
		2 < GEH < 5	17.6%
		5 < GEH < 10	16.2%
	Evening Peak (4:00-5:59pm)	GEH < 1	45.9%
		1 < GEH < 2	20.3%
		2 < GEH < 5	16.2%
		5 < GEH < 10	17.6%

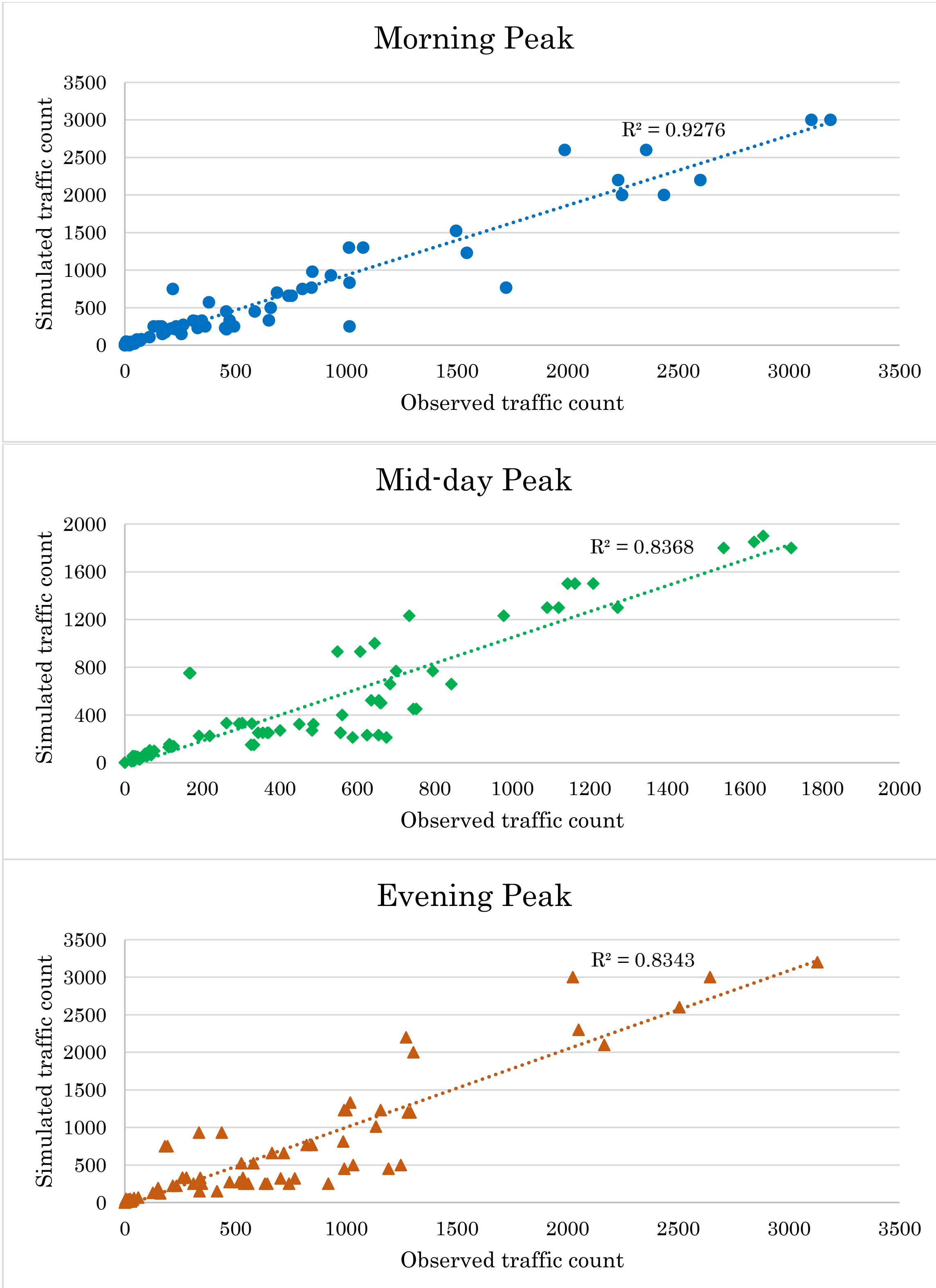


Figure 2-12 Comparison of Observed and Simulated Traffic Count after Calibration

The R^2 for three periods (morning, mid-day and evening peak period) are found as 0.93, 0.84, and 0.83 (Figure 2-12). The value of R^2 near to 1.0 means there is a strong correlation between simulated and observed field traffic count data i.e. the model exactly mimics the observed traffic count data. Conversely, R^2 near 0 means there is no correlation between field and simulated traffic count data. For this study, R^2 is above 0.8 for all time periods. Another goodness-of-fit measure, RMSE reflects the absolute deviation of the simulated and observed traffic volume. The average RMSE for three periods are estimated as 259.8, 238.9, and 360.2. The smaller values of RMSE implies that simulated truck counts conform to the observed counts with high accuracy. Another link volume-based statistic, GEH, is used to measure the goodness-of-fit of the model. This is a modified form of Chi-Squared statistic which is used to detect the relative difference between the simulated and observed traffic volume. A GEH value smaller than 1 represents an excellent match between simulated and observed traffic volume. A GEH value between 1 and 5 represents a good fit and a value between 5 and 10 is acceptable *(Chitturi, 2014; Oketch and Carrick, 2005)*. GEH values of less than 1 has been found for 50%, 44.6%, and 45.9% of traffic movement at three peak periods respectively and less than 5 for 87.7%, 83.8%, and 82.4% of total traffic movement. No movement has a GEH value greater than 10.

2.4 Results and Discussion

2.4.1 Results of Trip Generation and Distribution

The trip generation results reveal that among total truck traffic, the share of the light truck is 29%, 12% for medium trucks and 59% for heavy trucks. A representation of daily zonal trip production for passenger car and trucks is provided in Figure 2-13. From the result, it is clear that the model reflects the role of two ports, the intermodal terminal, Burnside, and Bayer’s Lake which are the major truck generators.

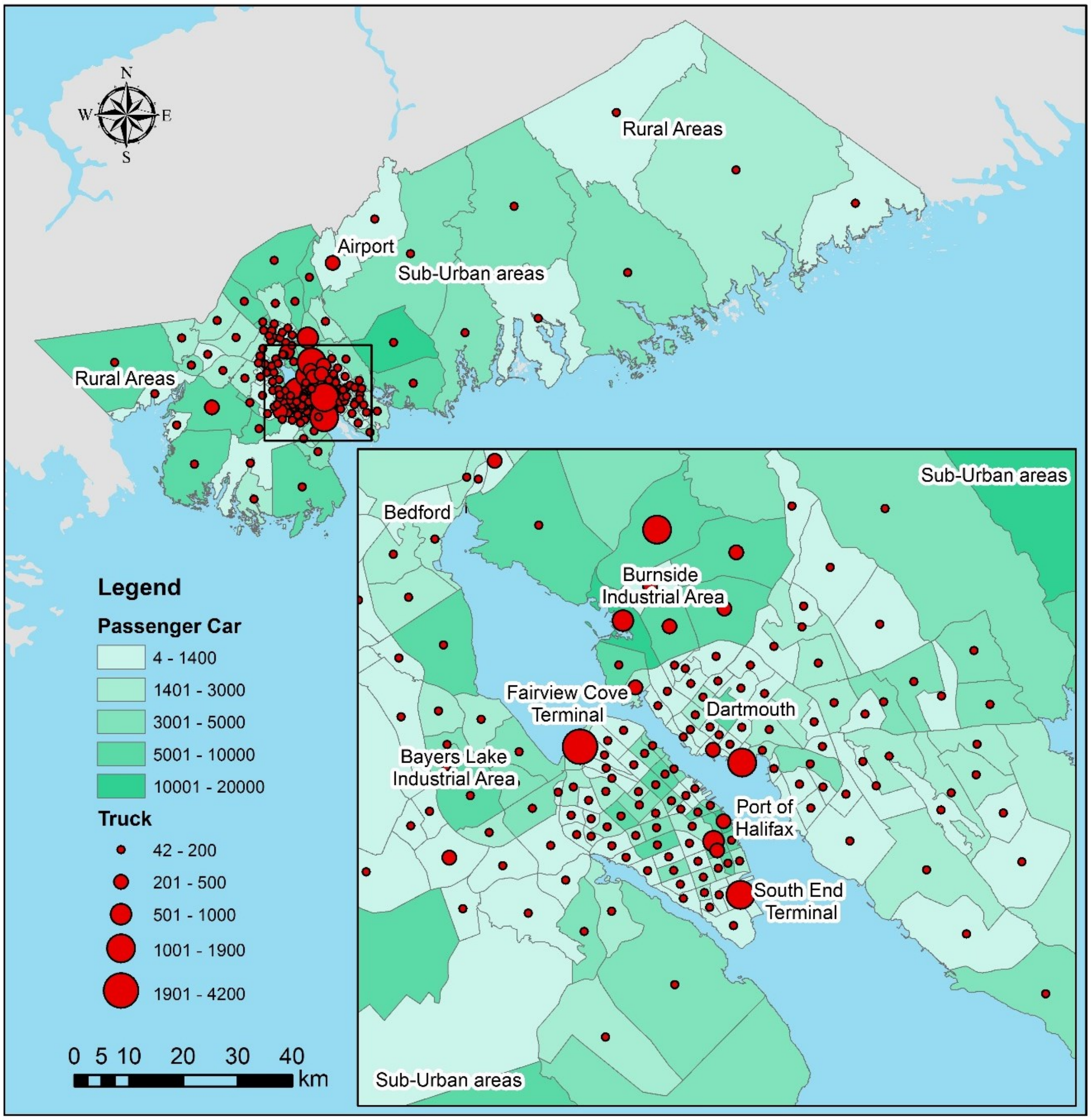


Figure 2-13 Distribution of Daily Trip Production by Different Vehicles at TAZs

Halifax peninsula and the core area of Dartmouth, also generate a significant number of trips. A total of 17% of port truck trips travel to or from Burnside within HRM. Additionally, 43% of total truck trips have an origin or a destination outside the HRM. Additionally, high number of passenger car in suburban area indicates the commuting traffic towards downtown core along with truck traffic. Population of rural area is very low comparing to urban and suburban areas resulting in a low number of passenger car trips production. The traffic composition comprises 95.06% passenger car and 4.94% trucks. Figure 2-14 shows the total trip production and attraction for evening peak period. Hourly trip production and attractions from each TAZ for a 24-hour period are enclosed in Appendix E. These 48 maps show the gradual changes of hourly trip production and attractions for a typical day.

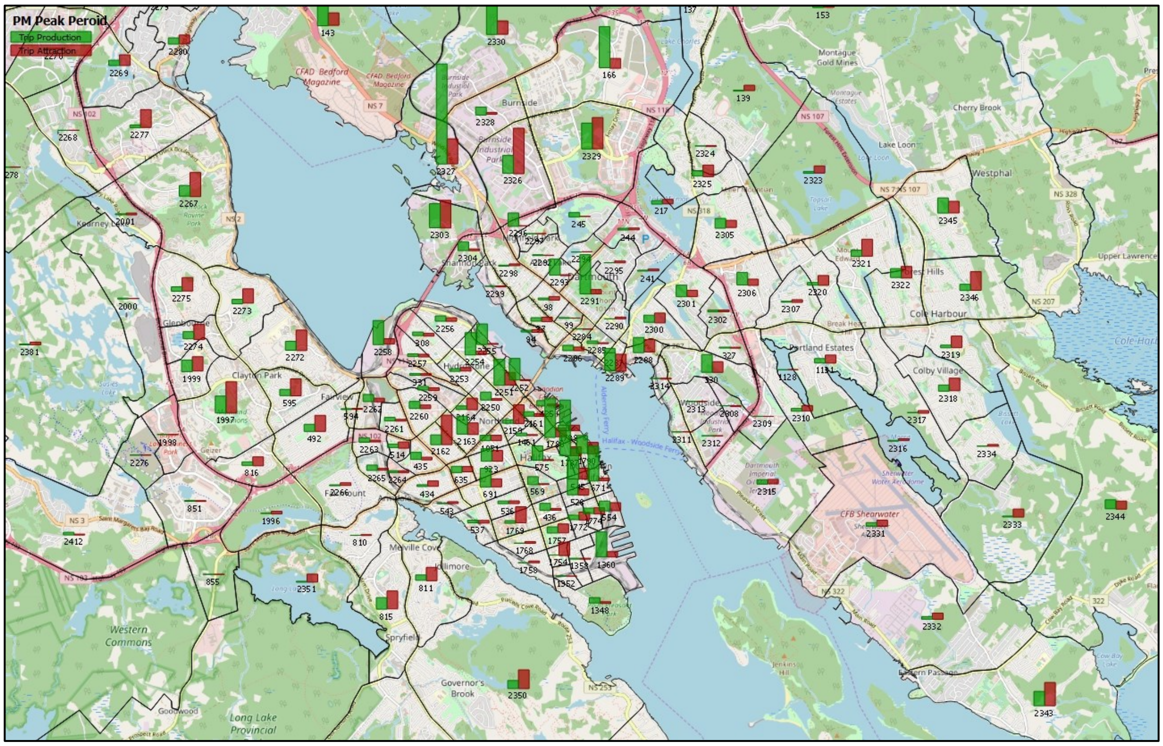


Figure 2-14 Trip Production and Trip Attraction at Evening Peak Period

In the case of long haul trips, majority of the production and attraction occurs at seaport, container terminals, intermodal terminal and airport. Similar spatial pattern is observed for both the production and attraction of long haul trip. Figure 2-15 shows daily production and attraction of long haul trips at different TAZs of Halifax.

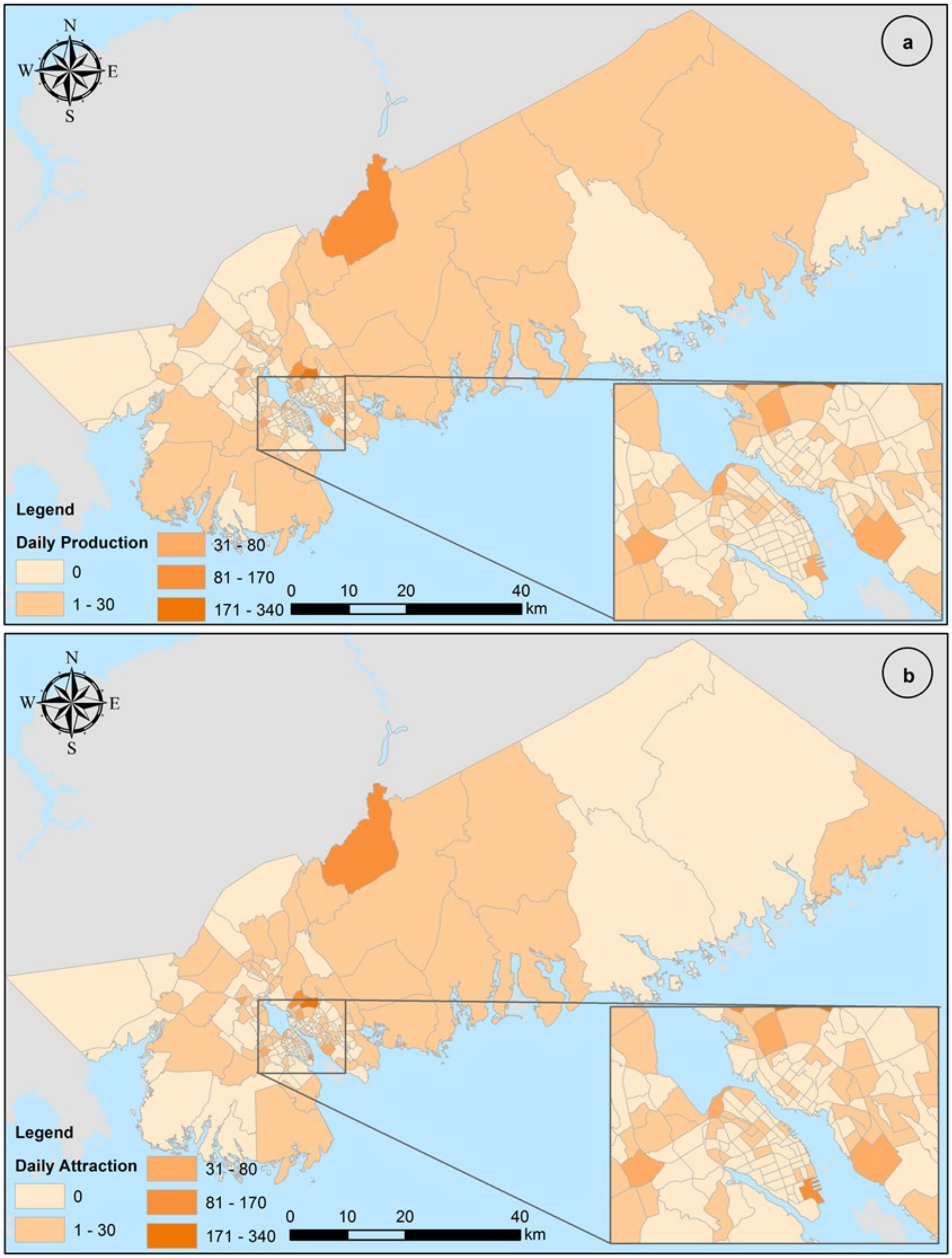


Figure 2-15 Daily (a) Production and (b) Attraction of Long Haul Truck

2.4.2 Results of Multiclass Traffic Assignment

This study examines link-based classified traffic volume, travel time, average speed, and vehicle kilometer travelled that result from the multiclass traffic assignment within the Halifax transport network model. Figure 2-16 is a representation of total traffic flow after multiclass traffic assignment within Halifax transport network model for Evening Peak period (for example). Volume for different modes is separately shown in Appendix F (Figure F-1). From the result, it is evident that vehicle flow is maximum in the urban core area, particularly across two bridges that connects twin cities, Halifax and Dartmouth. Almost 50% of the total traffic flows occur through these two connecting bridges, 27% flow occur on highways, major arterials share a traffic flow of 15%, and 4% by other collector roads.

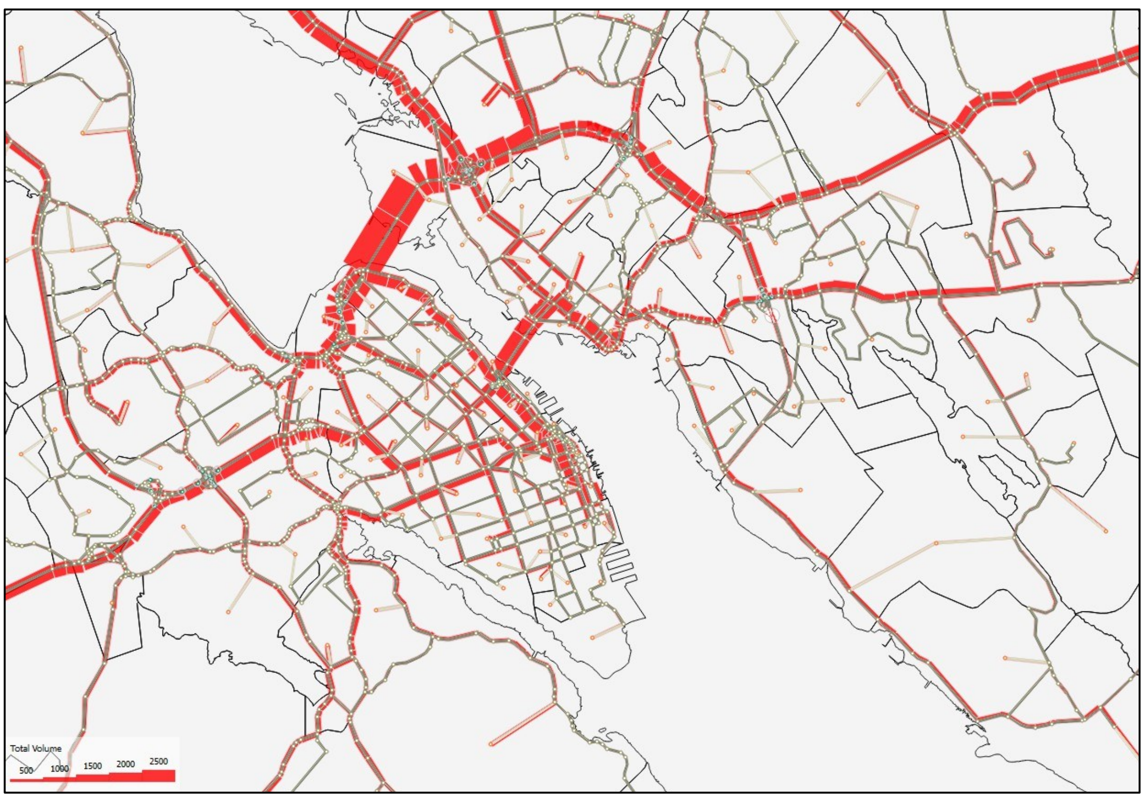


Figure 2-16 Traffic Flow at Evening Peak Period in Transport Network Model

This study also reports different attributes including Vehicle Hour Travelled (VHT), Vehicle Kilometer Travelled (VKT), vehicle volume and average speed within the network for each hour of traffic assignment. A representation of sample output of EMME is enclosed in Appendix F (Figure F-2) which shows resulting link attributes. Table 2-9 presents disaggregated results of these attributes for each mode separately. From this table it is evident that, total volume of passenger car is maximum during evening peak period from 4:00 to 4:59pm. Movement of light and heavy trucks is maximum in mid-day period ranges from 11:00am to 12:59pm. Movement of medium trucks is comparatively low all day around. The results also suggest that the average speed for passenger car ranges from 67.65 (at 4:00-4:59pm) to 71.6 (at 2:00-2:59am) kilometer per hour while the average speed for trucks ranges between 61.97 (in case of light trucks) to 73.96 (in case of heavy trucks) kilometer per hour. Heavy trucks may have a higher average speed than medium or light trucks since heavy trucks are allowed on high-speed highways that prohibit other categories of truck.

Table 2-9 Summary of Multiclass Traffic Assignment Results

Time	Mode	Vehicle Volume	Vehicle Hours Travelled	Vehicle Km Travelled	Average Speed (Km/H)
12:00-12:59am	Passenger Car	4,035	188,582	51,989	69.62
1:00-1:59am	Passenger Car	1,189	56,100	38,178	70.48
2:00-2:59am	Passenger Car	**851**	**38,227**	**10,253**	**71.6**
3:00-3:59am	Passenger Car	3,566	163,507	44,826	69.6
4:00-4:59am	Passenger Car	7,847	368,512	101,361	69.12
5:00-5:59am	Passenger Car	11,480	554,201	153,159	68.72
6:00-6:59am	Passenger Car	30,040	1,473,199	405,766	68.35
7:00-7:59am	Passenger Car	39,911	2,038,078	556,429	68.01
	Light Truck	902	31,106	8,984	62.58
	Medium Truck	**697**	**23,013**	**6,712**	64.00
	Heavy Truck	938	43,118	13,669	73.52
8:00-8:59am	Passenger Car	47,711	540,357	662,776	67.75
	Light Truck	1,379	14,783	13,558	62.33
	Medium Truck	861	8,301	7,393	62.82
	Heavy Truck	1,322	19,924	27,602	73.17
9:00-9:59am	Passenger Car	35,271	1,794,415	494,133	68.19
10:00-10:59am	Passenger Car	29,377	1,442,606	397,653	68.35
11:00-11:59am	Passenger Car	23,619	1,136,543	311,825	68.33
	Light Truck	3,184	125,530	36,286	62.78
	Medium Truck	2,144	52,162	15,150	64.66
	Heavy Truck	**2,076**	**137,039**	**43,825**	73.71
12:00-12:59pm	Passenger Car	24,600	1,214,710	334,645	68.30
	Light Truck	**3,408**	**135,796**	**39,276**	62.89
	Medium Truck	1,944	45,802	13,355	64.80
	Heavy Truck	1,451	113,436	37,399	73.95
1:00-1:59pm	Passenger Car	18,894	925,886	256,411	68.45
2:00-2:59pm	Passenger Car	28,735	1,415,681	391,061	68.36
3:00-3:59pm	Passenger Car	37,152	1,888,641	519,981	68.19
4:00-4:59pm	Passenger Car	**49,313**	**2,639,846**	**705,101**	**67.65**
	Light Truck	1,484	54,062	14,738	**61.97**
	Medium Truck	1,381	53,975	14,717	62.34
	Heavy Truck	1,590	143,830	48,032	**73.96**
5:00-5:59pm	Passenger Car	39,627	2,026,622	554,369	68.04
	Light Truck	1,314	48,623	13,616	62.18
	Medium Truck	869	33,644	9,441	62.88
	Heavy Truck	1,198	66,228	20,639	73.13
6:00-6:59pm	Passenger Car	30,150	1,483,009	409,152	68.35
7:00-7:59pm	Passenger Car	27,305	1,344,804	371,898	68.37
8:00-8:59pm	Passenger Car	19,397	949,836	262,995	68.45
9:00-9:59pm	Passenger Car	15,511	759,271	210,476	68.47
10:00-10:59pm	Passenger Car	10,085	483,037	133,596	69.05
11:00-11:59pm	Passenger Car	6,343	293,255	80,863	69.25

Figure 2-17a shows the total daily link volume of all vehicles and Figure 2-17b shows the total daily link volume of long haul trucks. In these schematics, thicker lines represent higher measures of implied traffic volume and vice versa. It is evident that the road network in the urban core of Halifax experiences higher traffic flow, which is 53.37% of total traffic. Figure 2-17a shows that Highway 102, the major arterial corridor of Barrington Street and the Mackay Bridge facilitated most truck movement. As shown in Figure 2-17b, highways experience a major portion of heavy truck movement travelling outwards through nearby towns to the Canadian hinterlands in Quebec, Ontario, New Brunswick (i.e., highway 102 bound). The assignment results suggest that, 65%, 22%, and 13% of total heavy truck movement occurs through three external zones located in Truro (highway 102 bound), Windsor (highway 101 bound), and Bridgewater (highway 103 bound) respectively. As stated earlier, trucks can deliver goods in Cape Breton, Prince Edward Island, other parts of Canada and/or outside of Canada through Truro and the southwestern part of Nova Scotia can be served through two other external zones i.e. Windsor and Bridgewater. The assignment results also suggest that only 12.5% of total heavy truck flow occurs in the urban core network while 60.4% occurs in suburban area. This result is reasonable as most of the industrial and commercial areas are located within suburban areas. The port and the airport are two special generators of long haul truck which has been reflected in truck flows on nearby links. The results offer insights into the impacts of heavy truck movement on traffic congestion in the network.

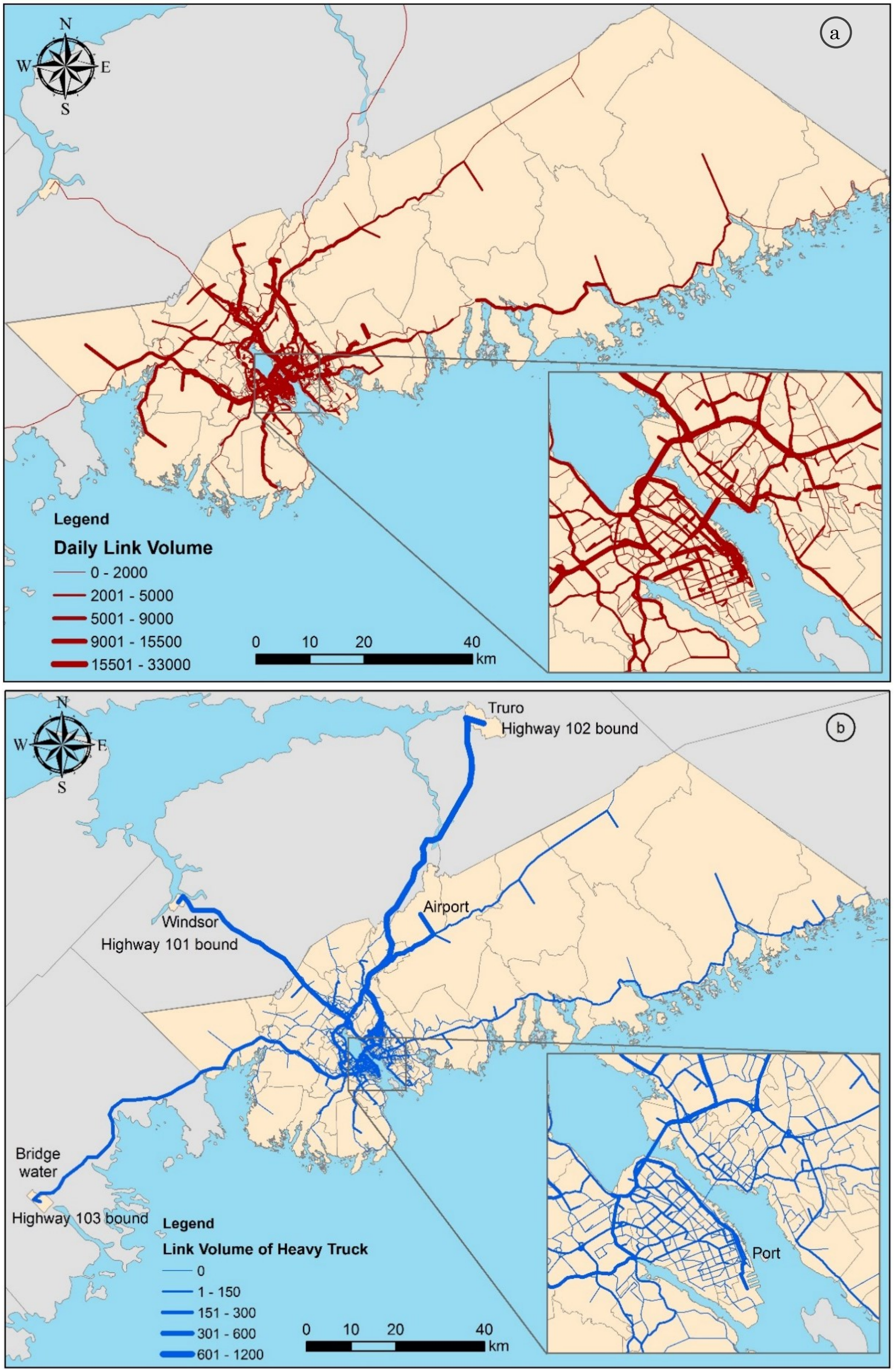


Figure 2-17 Daily Total Link Volume of (a) All Vehicles and (b) Heavy Trucks

2.5 Conclusion

This study developed a trip-based multiclass travel demand forecasting model to estimate different traffic flow attributes and congestion in the Halifax transport network. The study quantified the spatial and temporal evaluation of commercial vehicles movement for the port city of Halifax. The uniqueness of the developed multiclass traffic assignment model is that it incorporates commercial vehicle movements along with the passenger car movements simultaneously within the transport network model. Moreover, this chapter significantly contributes to the extensive calibration and validation of the model at nine key locations of downtown core for six hours. The validation result shows an acceptable goodness -fit -of the model measured in terms of R^2, GEH and RMSE values. The traffic assignment results reveal that the vehicle flow is maximum in the urban core area, particularly across two bridges that connects twin cities, Halifax and Dartmouth. Almost 50% of the total traffic flows occur through these two connecting bridges. The high number of passenger car trips generating from the suburban area indicates the morning commuting traffic flow towards the downtown area. The evening peak period is the most critical as the maximum number of vehicles is present during this period in the network. Travel demand modeling results for commercial vehicles suggest that a total of 17% of port truck trips travel to or from Burnside within HRM. Additionally, 43% of total truck trips have an origin or a destination outside the HRM. Movement of light and heavy trucks is maximum in mid-day period while the movement of medium trucks is comparatively low all day around.

The transport network modeling in this chapter has some limitations. Due to unavailability of detailed commercial vehicle survey dataset, simpler method, for instance, Quick Response method was used. The model takes a trip-based approach. However, a tour-based approach could be useful for modeling the trip chaining behaviour and intra-zonal movement of commercial vehicles. Further firm-level truck movement data collection is required to perform a tour-based modeling.

The model results can be used for an emission model to estimate the disaggregated (i.e., diesel-fuelled and gasoline-fuelled emission) emission contributed by all modes in the network. The multiclass traffic network model developed in this chapter can be used by the policy makers to implement different regional-level transport policies for instance, emission reductions, and /or congestion pricing in future. This information will be useful for tracking progress to meet the target outlined in the sustainable transportation strategy 2013 adopted by Nova Scotia Department of Energy.

Chapter 3

Development of an Enhanced Transport Network Model Including Tour-based Local Delivery Truck[2]

3.1 Introduction

Commercial vehicles comprise a substantial portion of all traffic movements in the urban road network *(Hunt and Stefan, 2007)*. However, freight transportation has not received the same level of attention as passenger transport, despite its linkages to economic development and urban growth *(Smart Growth Network, 2011; Ziomas et al., 1995; Grenzeback et al., 1989)*. At a local level, delivering goods adds additional substantial number of trucks to the existing large volume of commercial vehicles within the urban network. Results from a recent Calgary survey reveal that above 50% of urban commercial vehicle trips are made by light trucks *(Hunt and Stefan, 2007).* Such rise in the number of commercial vehicles will increasingly contribute to the traffic congestion and the environmental pollutions *(Smart Growth Network, 2011; Ziomas et al., 1995).* This situation could further deteriorate as local delivery trucks add to the existing daily traffic, resulting in an increase in local congestion and vehicular emissions. Commercial vehicles are often larger than passenger cars, thus they can have greater impacts on road pavement wear, traffic congestion, traffic flows, Greenhouse Gas (GHG)

---

[2] This chapter is partially derived from the peer-reviewed conference paper, Bela, P. L., and Habib, M. A. (2019). "Commercial Vehicle Movement Network Modeling for Halifax, Canada: A Tour-Based Model for Local Truck Delivery". *Proceedings of the 98th Annual Meeting of Transportation Research Board*, Washington, D. C., January 13-17, (No. 19-01657)

emissions and other vehicular emissions depending on dimensions, weight and engine power *(Highway Capacity Manual, 2000; Ziomas et al., 1995; You, 2012).*

In recognition to the importance of passenger transport systems and the effects of commercial vehicle movement, it is important to model both systems simultaneously when developing a comprehensive multiclass transport network model for policy analysis and planning in urban areas *(Sharman, 2014).* This study intends to develop both the trip-based passenger car and tour-based commercial vehicle demand model to improve the estimation of the congestion and emission in the network. There is a growing number of commercial vehicle movement models in recent years; however, delivery truck movement modeling has not yet been realized in many models due to the unavailability of firm-level data and overreliance on trip-based modeling. Modeling urban delivery truck movement is different than other long haul commercial vehicle movement. Urban delivery trucks involve serving multiple intrazonal trips for local delivery at different delivery locations *(Tozzi, 2013; You, 2012)*. As a result, without a tour-based truck movement model, such trip chaining behavior of urban truck travel patterns is difficult to capture within transport network models *(Comi, 2012; Tozzi, 2013; You, 2012).* There is a clear gap in tour-based delivery truck movement modeling that incorporates trip chaining pattern of commercial vehicle movement. In general, in port cities such as Halifax, trucks dominate the freight market due to their flexibility, cost effectiveness and minimum loss and damage *(Baegan et al., 2007)*. The modeling of delivery truck tour movement along with passenger car component in Halifax is necessary, as the port, two container terminals and a large concentration of industries and service centers are located within the urban core of the city.

Therefore, the objective of this chapter is to develop a tour-based delivery truck movement model utilizing a large firm-level data set for multiclass traffic assignment for the year of 2016. It also updates the Halifax passenger car demand forecasting model *(Bela and Habib, 2018b)* by utilizing 2016 Nova Scotia Travel Activity (NovaTRAC) Survey dataset. The novelty of this study is that, it integrates a tour-based local delivery truck movement model with a trip-based passenger car movement model within a single transport network modeling platform. In addition, the proposed framework incorporates essential elements of urban commercial vehicle movements, such as service delivery, intrazonal movement and trip-chaining behavior. First, passenger car and long-haul truck trips are estimated utilizing a trip rate method and GPS tracking information respectively. Then, local delivery truck tours are developed employing a Monte Carlo simulation technique. Finally, this study utilized the Halifax Regional Transport Network Model to perform a multiclass traffic assignment of passenger cars, delivery trucks and long-haul trucks within a simulation platform. The model results generated link-based volume of all modes within the Halifax Regional Municipality (HRM).

3.2 Literature Review

Research on commercial vehicle demand modeling has significantly increased in recent years due to the detrimental effects on congestion, environment and energy security *(Samimi et al., 2010; Bryan et al., 2008)*. Pendyala et al. *(2000)* extensively reviewed the existing commercial vehicle travel demand models across North America. While there is a growing body of research on urban commercial vehicle movement, there is limited research that addresses delivery truck tour modeling issues *(Sharman, 2014; Bryan et al., 2008; Hunt and Stefan, 2007; Stefan et al., 2005; Ambrosini and Routhier, 2004; Grenzeback et al., 1989)*. The majority of the regional and urban transport network models utilize either the growth factor or four-stage modelling approaches for the estimation of commercial vehicle demand to be used as background traffic in a passenger car network model *(Sharman, 2014; Sharman and Roorda, 2011, Gong and Guo, 2011).* These methods are not data intensive and can easily be implemented to estimate regional truck demand *(Sharman, 2014; Beagan et al., 2007; Pendyala et al., 2000)*. Large scale models often simplify commercial vehicle demand within the modeling framework. For example, services are not considered in commodity-based four-step truck trip generation model in Los Angeles *(Fischer et al., 2005),* but approximately 45% of all urban commercial vehicle movements are made to provide local service according to a recent Calgary survey *(Stefan et al., 2005)*. There is a significant number of trip-based truck movement model in the existing literature *(Bassok et al., 2011; Cavalcante and Roorda, 2010; Russo and Comi, 2010; Friesz et al., 2008; Holguín-Veras et al., 2004; Xu et al., 2003; Russo and Comi, 2002)*. The majority of the models take a trip-based approach to model urban truck movement, which cannot represent tour-based nature (i.e. intrazonal trips, trip-chaining behaviour) of urban commercial vehicle movement *(Tozzi et al., 2013; You and Ritchie, 2012; Comi et al., 2012; You, 2012; Samimi et al., 2010; Wang and Holguin-Veras, 2008; Donnelly et al., 2008; Hunt and Stefan, 2007; Hensher and Figliozzi, 2007; Hensher and Puckett, 2005; Boerkamps, et al., 2000)*. Studies found that, on average, approximately 4.9 – 12.2 trips are produced for each tour *(Greaves and Figliozzi, 2008; Hunt and Stefan, 2007; Figliozzi et al., 2007; Holguin-Veras and Patil, 2005; Vleugel and Janic, 2004)*. These one-to-many distributions of delivery trucks have an extensive impact on vehicle counts in urban areas *(You, 2012; Beagan et al., 2007; Outwater, 2005)*. A trip-based approach is not suitable to mimic such trip chaining behavior of commercial vehicles *(Tozzi, 2013; Comi et al., 2012; You and Ritchie, 2012; You, 2012)*.

Consideration of tour-based truck movement modeling is practically needed, but methodologically sophisticated. To accurately capture tour routing in an urban transport network requires a detailed commercial vehicle movement network model, which can assign trucks with other available modes in the network to capture the effects of combined congestion. For example, Bela and Habib *(2018a, 2018b)* developed a regional transport network model for Halifax, Canada to examine multiclass traffic operation and estimate resulted emissions. They employed a four-stage modeling approach to simulate truck trips in the network which cannot capture trip-chaining behavior of local delivery truck movement in the network. The main challenge of modeling tour-based truck movement is limited access to related micro-level data *(Regan and Garrido, 2001)*. To adequately estimate the truck tour production from a firm-level dataset, detailed information, including firm locations, and their number of employees, is required, as they influence the number of truck trips generated from that firm *(Ortúzar and Willumsen, 2011; Hunt and Stefan, 2007; Kawamura et al., 2005)*. Determining tour from survey-based approaches is challenging and often expensive *(Sharman and Roorda, 2011; Roorda et al., 2008)*. On the other hand, GPS information provides high quality data, but it is prohibitive for all truck types including delivery trucks *(Sharman, 2014; Sharman and Roorda, 2011; Greaves and Figliozzi, 2008; Figliozzi et al., 2007)*. Greaves and Figliozzi *(2008)* studied issues surrounding the collection and use of GPS data as a method to provide information on commercial vehicle tours within an urban setting. They presented implementation issues with the data collection, processing of raw GPS data and tour results. Figliozzi et al. *(2007)* also analyzed truck tour data obtained from an eight-month travel diary of truck movement. Hunt and Stefan *(2007)* employed a Monte Carlo simulation technique to develop tour-based microsimulation model for Calgary, Canada. Truck tour generation is not homogeneous, it may vary across different business establishment types *(Bastida and Holguín-Veras, 2009)*. For example, truck trip generation is relatively high for retail and service sector *(Sánchez-Díaz, 2017; Hunt and Stefan, 2007)*. Additionally, the process to calibrate and validate the delivery truck tour model is unknown. Therefore, there is a clear gap in tour-based modeling of delivery truck movement including detailed calibration and validation of the model. This study bridges the gap in literature by proposing a tour-based delivery truck movement network modeling framework. In recognition of the aforementioned literature this study extends an urban truck network model in conjunction with passenger car movement model taking a traditional trip-based approach. Following this, it develops a tour-based delivery truck movement model for Halifax, which can assign truck tours within a multiclass traffic assignment platform. A Monte Carlo simulation technique is adopted to determine per-employee tours and to construct key tour attributes, including tour start time, start location, next delivery stop location, and tour end time. This study utilized an Info Canada data set to generate number of tours at TAZs for different types of establishments. The data set contains 27,851 firm records with information about firm type, location, employee number and other details. A detailed calibration and validation of the enhanced travel demand forecasting model was then performed by utilizing a video image processing-based traffic count data at different locations of the Halifax Regional Municipality. Lastly, a link surcharge method is used to calibrate the certain link attributes, including cost. The model results are represented in terms of spatial and temporal variation of commercial vehicle movement, as well as link-based traffic flows.

3.3 Modelling Approach

This study develops a comprehensive framework of a multiclass traffic assignment modeling for Halifax, Canada. Figure 3-1 shows three components of the framework which include (i) passenger car demand modeling, (ii) local delivery truck demand modeling, and (iii) long haul truck demand modeling component. The study adopts a novel approach of Monte Carlo simulation technique to develop the local delivery truck tour model using a rich farm level data source. Moreover, it improves the passenger car demand modeling using a recent 2016 Nova Scotia Travel Activity (NovaTRAC) Survey conducted by Dalhousie Transportation Collaboratory (DalTRAC). The detailed description of the modeling components is presented in the following sections.

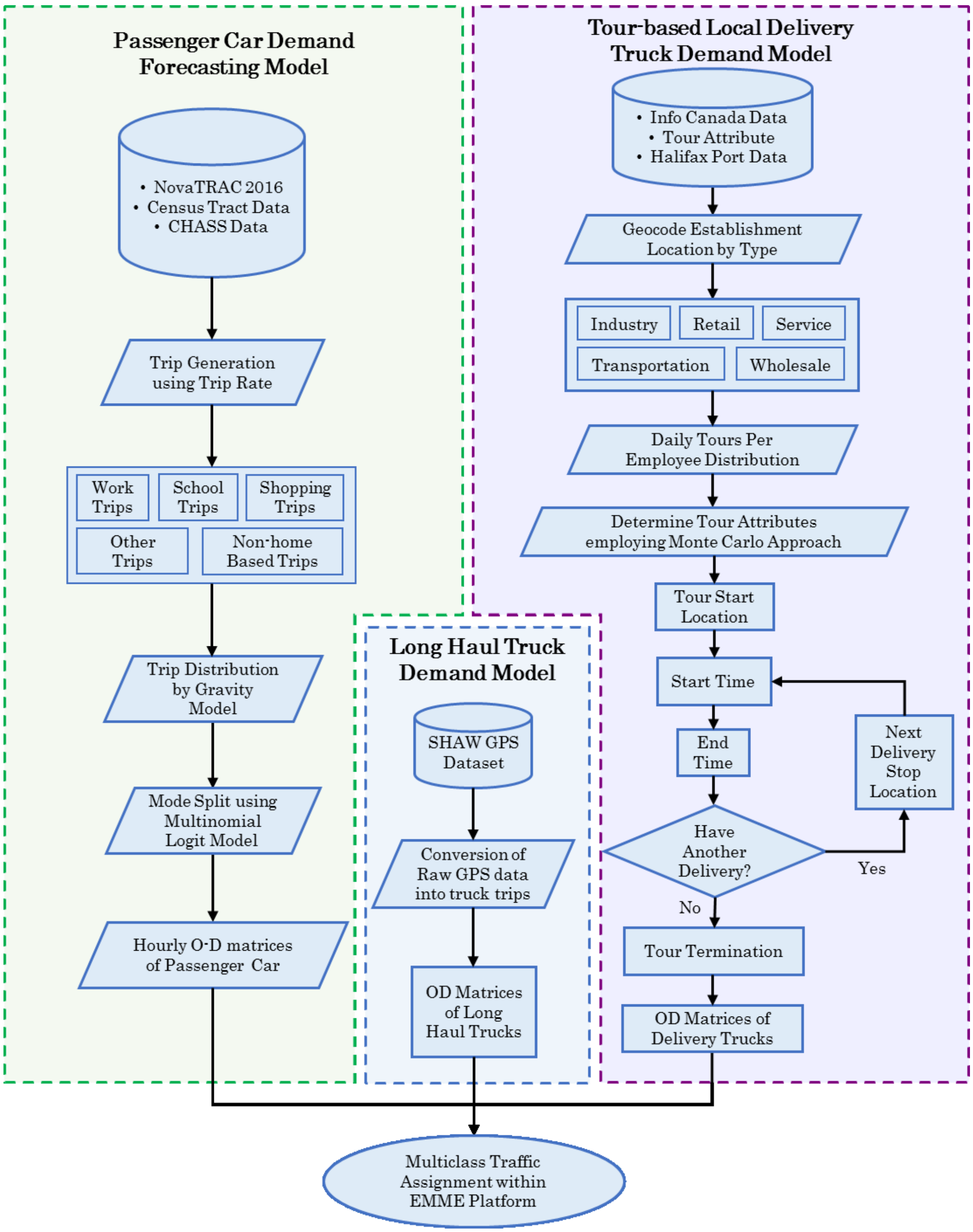


Figure 3-1 Framework of Enhanced Travel Demand Model for the Year of 2016

3.3.1 Passenger Car Demand Forecasting Model

A four-stage modeling approach is used to develop the travel demand model of passenger car for the year of 2016. However, a newer dataset which was obtained through a Nova Scotia Travel Activity (NovaTRAC) survey in 2016 is utilized in this model. The newer dataset facilitates determining the mode-specific trip rates for different trip purposes. Therefore, a trip rate analysis method is used for developing trip generation model in this chapter. To determine the share of the travel demand by modes, corresponding trip rates are applied to the demographic attributes of TAZs. Like previous chapter, five types of trips based on trip purposes are used for the development of the 2016 travel demand model. The detailed modeling approach is described in the following sections.

3.3.1.1 *Data Used*

This study used multiple data sources to develop the 2016 travel demand forecasting model. As mentioned earlier, NovaTRAC survey data is used to estimate the trip rate for each TAZ. This household travel activity survey was conducted by Dalhousie Transportation Collaboratory (DalTRAC) in partnership with the Province of Nova Scotia and Halifax Regional Municipality (HRM). The survey was designed focusing in five key areas such as (i) household characteristics (ii) household members' information (iii) health information (iv) attitudinal questions and (v) a 24-hour travel activity log of each member. The respondents were asked to provide a variety of information for each area in the survey. A list of information types under each area included in the survey is shown in Table 3-1. The survey collected information regarding the household and its members, household vehicles, and a 24-hour travel activity log. This information includes: number and types of vehicles, residential location, and type, household ownership status, household size. Moreover, it includes, age, education, employment, annual income, attitudes and lifestyle preferences of all household members. The 24-hour travel activity log includes: household members' trip locations, arrival and departure time for each trip, accompanying person, mode used, and different purposes for trip making.

Table 3-1 Information of the NovaTRAC 2016 Survey

Criteria	Collected Information
Household Characteristics	• Number and type (make and model) of vehicles available for personal use • Number of bicycles • Public transit use • Active transportation use • Location of residence, ownership status and type of dwelling • Household size and income
Household Members Information	• Demographics (age, education, employment, etc.) • Possession of a valid driver's license and transit pass • Primary mode for commuting • Distance and travel time of one-way commute
Health Information	• General health description • Mental health description • Physical activity level
Attitudinal Questions	• Transportation and vehicle preferences • Feelings towards commuting • Feelings towards their neighborhood • Concern towards the natural environment
24-hour Travel Activity Log	• Location of each place the household member traveled • Arrival and departure time for each location • Mode of transportation used • Reason for making the trip

NovaTRAC 2016 is a web-based survey system which comprises of two separate but connected interfaces: the front-end and back-end. The user front-end interface allows the user to view and complete the travel activity questions online. Any available browser on systems such as smartphone, and personal computers can easily be used to participate and complete the survey. The back-end is the DalTRAC administrative server that includes the data processing script and a database designed to collect and store survey responses. The survey yielded in total 591 Household and 647 individual travel records. To acquire information regarding dwellings, socio-economic and demographic attributes, Census Tract (CT) data is utilized. Statistic Canada is used to obtain the census digital boundary in a shapefile format.

3.3.1.2 *Trip Generation*

The trip generation model in this chapter is developed by estimating trip rates and the number of dwelling units for each TAZ. The trip rate estimation process is described below under the section 'Trip Rate Analysis'. The number of dwelling units for each TAZ is estimated as described under 'Data Processing' after the section of Trip Rate Analysis.

Trip Rate Analysis

To generate the trip rates for Home-Based Work (HBW), Home-Based School (HBS), Home-Based Shopping (HBSh), Home-Based Other (HBO) and Non-Home-Based (NHB) trip types, origin-destination activities from the 2016 NovaTRAC Survey data are re-coded at TAZ level. "Working at home (for pay)" and "All other activities at home (e.g. sleeping, meals, etc.)" are recoded to a value of 1 (Home), "Work/job (for pay or volunteer)" and "All other activities at workplace" are recoded to a value of 2 (Work), and so on. Next, a conditional IF statement is used to categorize each trip into HBW, HBS, HBSh, HBO or NHB, which are divided into two legs. For example, the first leg of a HBW trip is counted if it originates at home and is destined to work. Subsequently, the second leg of an HBW trip is counted if it originates at work and is destined to home. The conditional classification process is continued for aforementioned trip types. To consolidate the classified trip counts, a pivot table is used to summate all trips at home-based ends (production) and non-home ends (attraction) for each individual from the NovaTRAC survey sample. Lastly, to generate trip rates, summated counts in the pivot table are averaged for each trip type. Classified trip rates obtained in this process are presented in Table 3-2.

Table 3-2 Classified Trip Rates for All Trip Types

Trip Types	Trip Rates
Home to Work Trip	0.601
Work to Home Trip	0.539
Home to School Trip	0.101
School to Home Trip	0.087
Home to Shopping Trip	0.081
Shopping to Home Trip	0.16
Home to Others Trip	0.469
Others to Home Trip	0.475
Non-home based Trip	0.572

Data Processing

To convert 2016 Statistics Canada Census Profile attributes of the Halifax Regional Municipality (HRM) from Dissemination Area (DA) level to Traffic Analysis Zone (TAZ) level, DA level data is downloaded from the CHASS Data Centre. Next, the 2016 Census Digital Boundary File of DAs is downloaded from the Statistics Canada website in the shapefile format. The boundary file is then clipped in ArcGIS to the HRM to mirror the boundary of the TAZ file used in the previous chapter. Since the DAs do not nest directly within TAZs, the Tabulate Intersect tool is used to generate a table which summarizes the DAs within a TAZ and the proportion of their areas within the TAZ (Figure 3-2).

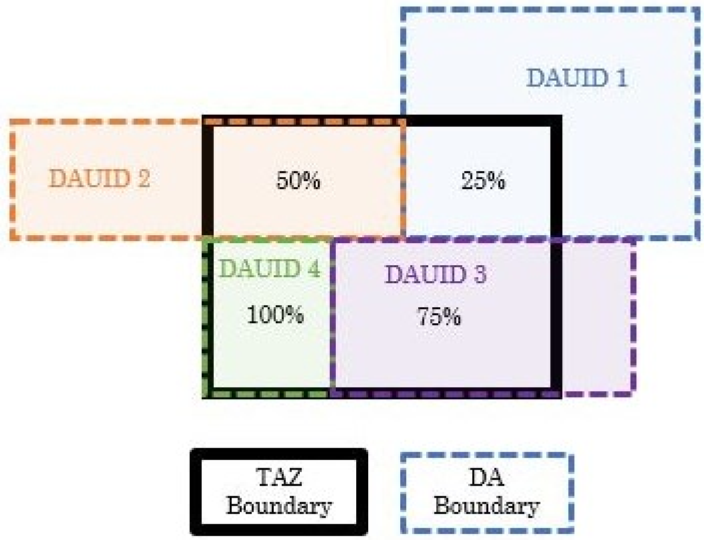


Figure 3-2 Visual Representation of the DA to TAZ Conversion Process for a Simplified Sample Attribute

For simplicity, assume that TAZ X contains four DAs within its boundary: 1, 2, 3 and 4 with 25%, 50%, 75% and 100% of their respective areas within the TAZ (Figure 3-2). To facilitate a simple join in Access, the DA level Census Profile data is streamlined in Excel, with DAUIDs in the first column and their attributes in subsequent columns. The DAUIDs from the Census Profile data table are then joined to the DAUIDs from the Tabulate Intersect table, linking the respective attributes. The resulting table is used as the conversion tool and saved as such. To convert the DA attributes to TAZ attributes, the DA attributes are multiplied by their respective proportions within the TAZ (Table 3-3). For simplicity, assume that TAZ X contains 25% of DA 1 within its boundary. Therefore, the assumption is that 25% of the dwellings from DA 1 are within the boundary of TAZ X. After the proportions are applied to each DA attribute in each TAZ, they are consolidated. For census attributes containing a total, such as the number of dwellings, the sum function is used to generate the final number of dwellings within a TAZ (Table 3-3).

Table 3-3 Attribute Estimation for DA to TAZ Conversion Process

DA Level Input				TAZ Level Output	
DA	DA_Within TAZ (% of Total DA Area)	DA_Attribute (# Dwellings)	New DA_Attribute (# Dwellings)	TAZ	TAZ_Attribute (# Dwellings)
1	0.25	100	25	X	250
2	0.50	100	50		
3	0.75	100	75		
4	1.00	100	100		

For census attributes containing an average, such as average income, the average function is used to generate the final average income within a TAZ. Lastly, the Excel Spreadsheet for the new census attributes is exported, where the first column contains TAZ IDs and their attributes in subsequent columns. The TAZ IDs from the new Spreadsheet are then joined to the TAZ IDs from the Halifax transport network shapefile in ArcGIS and solidified by exporting the layer. Finally, trip rates are multiplied by the number of dwellings in different TAZs to estimate the total trip production and attraction.

3.3.1.3 *Trip Distribution*

A gravity model described in the previous chapter is utilized to distribute the generated trips among TAZs. Trip distribution stage outputs the hourly O-D matrices which contains total 24 trips tables. Time of the day information is used to generate hourly seed O-D matrices which are modified through calibration and validation process in the traffic assignment stage of the transport network modelling.

3.3.1.4 *Mode Split*

NovaTRAC 2016 survey data provides information regarding different trip purposes made by different modes (Table 3-4). From an aggregated analysis of the survey, it has been found that auto driver mode performs the significant portion of the work and non-work trips. For example, 72.3% of the work trips and 62.3% of the non-work trips are made by auto drivers in the year of 2016.

Table 3-4 Mode Split for the Model Year 2016

Mode Used	Modal Share for Work Trips (%)	Modal Share for Non Work Trips (%)
Auto Driver	72.3%	62.3%
Auto Passenger	8.0%	5.0%
Transit	6.3%	11.3%
Walk	8.8%	14.6%
Bike	4.6%	6.8%

The 24-hour travel activity log obtained from the survey is utilized to estimate the mode wise trip rates. Thereby, mode choice is embedded in the estimated trip rates in the case of developing 2016 travel demand forecasting model.

3.3.2 Commercial Vehicles Demand Forecasting Model

Unlike the previous model year, this model takes a tour-based approach for modelling delivery truck movements. For this study delivery truck yields both light and medium trucks. Movement of heavy trucks are modelled for long haul trips only. Therefore, this study considers two truck types: delivery truck, and long haul truck. This study utilized Monte Carlo simulation technique to determine several tour attributes. Detailed procedure to develop the tour-based delivery truck movement model is explained in next sections.

3.3.2.1 *Data Processing*

To develop local delivery truck tour, this study utilizes a large Info Canada Business Establishment dataset for the year of 2018. This dataset is very rich and reliable with 12,877 detailed firm records, including a 7-digit NAICS (North American Industry Classification System) code located in HRM. This is a subset of a full data set of 27,851 firm records for the province of Nova Scotia (NS). This data set provides detailed information about establishment name, type of establishment, geographic location, total number of employees, sales volume, year of establishment, credit rating and their expense. These information are significantly useful to estimate truck tour generation by TAZs and establishment types. There are twenty-four types of establishments in total. All establishments are re-grouped into five broad categories: Industry, Retail, Service, Transportation and Wholesale using their NAICS code as shown in Table 3-5.

Table 3-5 Classification of Five Establishments (parenthesis numbers indicate 2-digit NAICS code)

Establishment Types	Elements
Industry	• Agriculture, Forestry, Fishing and Hunting (11) • Mining and Oil and Gas Extraction (21) • Construction (23) • Manufacturing (31 to 33)
Retail	• Retail Trade (44,45)
Service	• Utilities (22) • Information and Cultural Industries (51) • Finance and Insurance (52) • Real Estate and Rental and Leasing (53) • Professional, Scientific and Technical Services (54) • Management of Companies and Enterprises (55) • Administrative and Support, Waste Management and Remediation Services (56) • Educational Services (61) • Health Care and Social Assistance (62) • Arts, Entertainment and Recreation (71) • Accommodation and Food Services (72) • Public Administration (92) • Other Services (except Public Administration) (81)
Transportation	• Transportation and Warehousing (48, 49)
Wholesale	• Wholesale Trade (41)

Each of the 27,851 establishments are geocoded using their exact longitude and latitude value. Later, they are spatially joined with the developed Halifax Transport Network Model to determine the number of employees for each type of establishment within each TAZ which is shown in Figure 3-3. Figure 3-3 reports, higher number of employees working within the urban core specifically near port. A summary of the data collected from Info Canada Business Establishment dataset for each establishment type according to area type is presented in Table 3-6. This table shows 63.5% of total firm falls in the service sector.

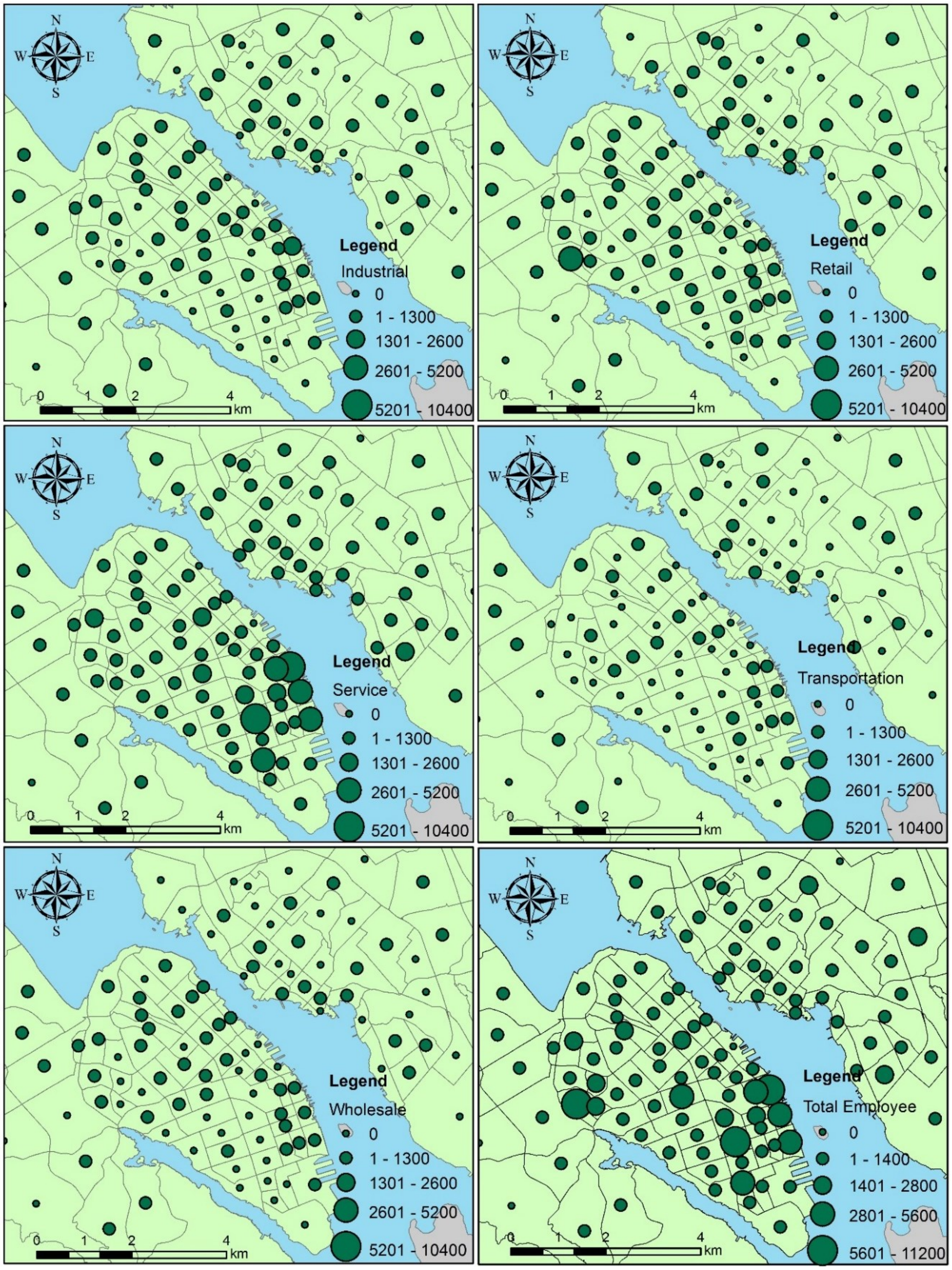


Figure 3-3 Number of Employee Distribution Over Urban Core of Halifax by Establishment Types

Table 3-6 Summary of Info Canada Dataset

Category	Area		Industrial	Retail	Service	Transportation	Wholesale	Unclassified
Number of Firm	Halifax	Urban Core	264	704	3279	67	121	38
		Suburban Area	797	909	3127	168	430	29
		Rural Area	335	198	843	50	66	13
	Other part of Nova Scotia		2162	3058	10032	386	706	70
% of Total Firm in Halifax			12.2%	15.8%	63.4%	2.5%	5.4%	0.7%
Number of Employee	Halifax	Urban Core	5284	13042	131006	1144	848	300
		Suburban Area	12794	18053	35819	6888	7151	43
		Rural Area	2632	1816	6646	6132	539	15
	Other part of Nova Scotia		24072	282991	95008	3645	9739	17
% of Total Employee in Halifax			8.3%	13.2%	69.3%	5.7%	3.4%	0.1%
Total Sale Volume (in $1000)	Halifax	Urban Core	1,619,934	2,333,517	21,353,563	126,624	652,076	-
		Suburban Area	3,447,387	5,141,854	3,175,215	1,757,788	4,164,542	-
		Rural Area	790,548	540,569	517,797	341,790	362,998	-
	Other part of Nova Scotia		9,238,070	27,109,242	7,968,796	483,174	11,752,088	-
% of Total Sale Volume in Halifax			12.6%	17.3%	54.1%	4.8%	11.2%	0.0%

3.3.2.2 *Determination of Tours per Employee*

A Monte Carlo simulation approach is used to generate number of tours per employee for all 203,490 employees working in 12,877 firms within the HRM. Figure 3-4 reports the result obtained from Monte Carlo simulation identifying daily tours per employee by establishment types. This distribution is utilized to calculate the total number of daily tours for all five establishment types at each TAZ. Figure 3-4 shows that almost 45% of the employees in transportation sector has no effects on truck tour generation. This share ranges from 21%-33% employee in the case of Retail, service, wholesale and industry sector. A maximum of 0.5 tour per employee is observed for all establishment types.

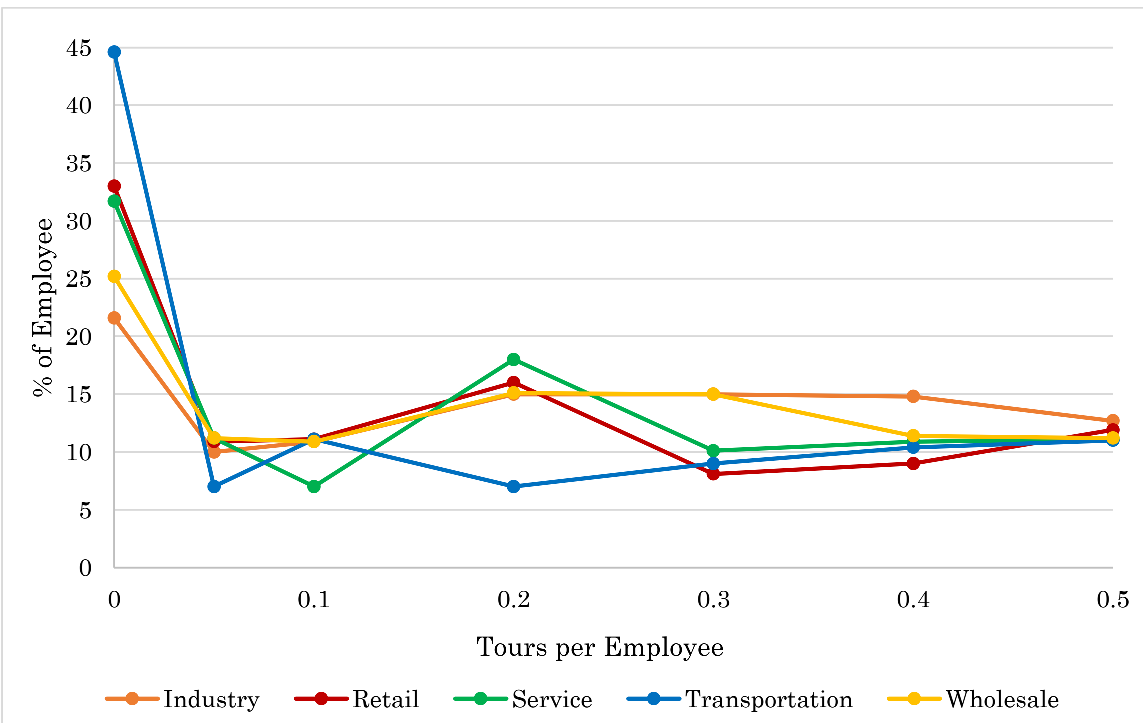


Figure 3-4 Daily Tours per Employee Distribution by Establishment Type

3.3.2.3 *Tour Formation and Distribution*

Based on a study of Southern California, You *(2012)* identified that a truck typically follows four possible tour pattern. A delivery truck tour is basically a series of truck trips made such that the destination of the first trip becomes the origin of second trip and continues in a recurring pattern until it finally returns to its origination location (Figure 3-5).

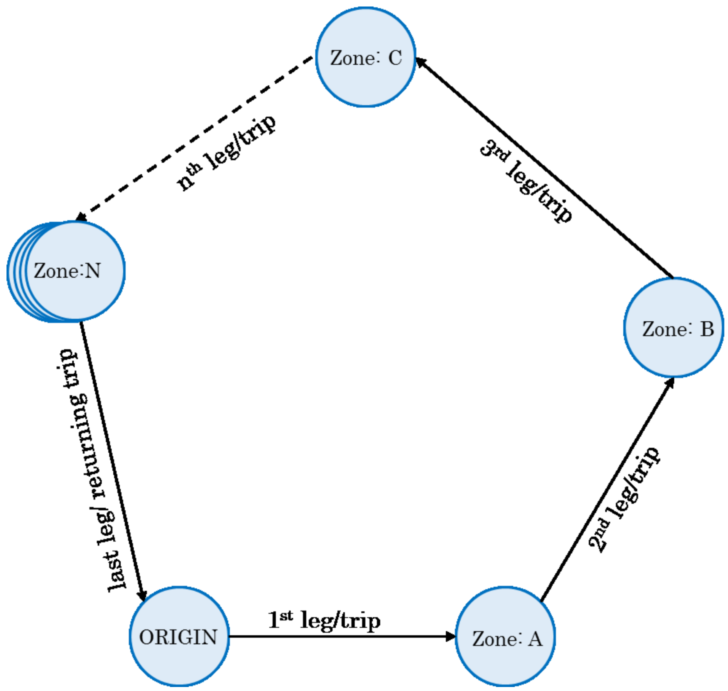


Figure 3-5 Formation of a Typical Delivery Truck Tour

You *(2012)* found that 34.36% of truck movements follow a tour pattern similar to this. Figure 3-5 illustrates a delivery truck tour involving four delivery stop locations and an origination location. The truck makes four trips to deliver goods at stops and a trip to return its origin. Each trip will be addressed as a tour leg in the rest of the thesis. A Monte Carlo approach is used to determine relevant tour attributes such as tour start time, start location, end time and next delivery stop locations for all tours. Next delivery stops are identified within an average tour leg distance which can vary per establishment type. The guidelines for average number of tour legs, average tour leg distance, average tour leg duration and average tour duration are provided in Table 3-7 *(Area, 2010).*

Table 3-7 Details of Tour Attributes

Industry type	Industrial	Retail	Service	Transportation	Wholesale
Average Tour Distance (km)	119.3	81.6	91	125.3	149.5
Average Tour Leg Distance (km)	17.5	16.2	20.7	14.2	22
Average Number of Legs	6.2	7.8	5	9	9.8
Average Tour Duration (hour)	9.0	5.8	5.7	11.4	13.7
Average Tour Leg Duration (min)	57.7	29.6	45.7	50.8	55.9

According to a Peel commercial vehicle survey, 88% of tour legs have a travel time duration below or equal to one hour. For simplicity, this study simulates each tour leg duration for one hour. This one hour includes both travel time and loading/unloading time for a truck. After an hour of simulation, each truck starts a new trip from its current location as part of the running tour in combination with a new truck which start their tour in the next hour from the same location. The majority of deliveries occur between 7:00am to 6:00pm *(Nuzzolo and Comi, 2014).* In Halifax, truck movement is negligible after 9:00pm based on SHW GPS data analysis *(Kevin et al., 2016).* Therefore, this study develops a fourteen-hour model spanning from 7:00am to 9:00pm for the Halifax Transport Network. Once the sequence of trips for each tour per establishment type is obtained from the Monte Carlo simulation, hourly origin-destination matrices are created. In total, seventy matrices are generated for five establishment types for fourteen hours of period. A Visual Basic Application (VBA) platform is utilized for data processing and analysis. Each establishment type was considered separately up to this step. After this step, hourly fourteen separate matrices are prepared for delivery trucks.

3.3.3 Preparation of O-D Matrices

Following the similar procedure that described in section 2.3.6 of previous chapter, twenty four O-D matrices are produced to represent the hourly trip flows made by passenger car for this model as shown in Figure 3-6. Long haul and delivery trucks are considered from 7:00am to 9:00pm that produces additional twenty-eight matrices. O-D matrices of trucks are converted into "Passenger Car Equivalent" matrices as described in section 2.3.6. In case of delivery and long haul trucks, PCE values of 2.0 and 2.5 are used respectively. Hourly long haul truck flow pattern is shown in Figure 3-7. After this step, in total fifty-two hourly O-D matrices (twenty-four for passenger car and twenty-eight for two truck types) are converted into a computer readable format. The detailed truck tour production results are discussed in section 3.4.3.2. As stated earlier, all O-D matrices describes trip table for 222 TAZs hence, the dimension of all O-D matrices are 222x222.

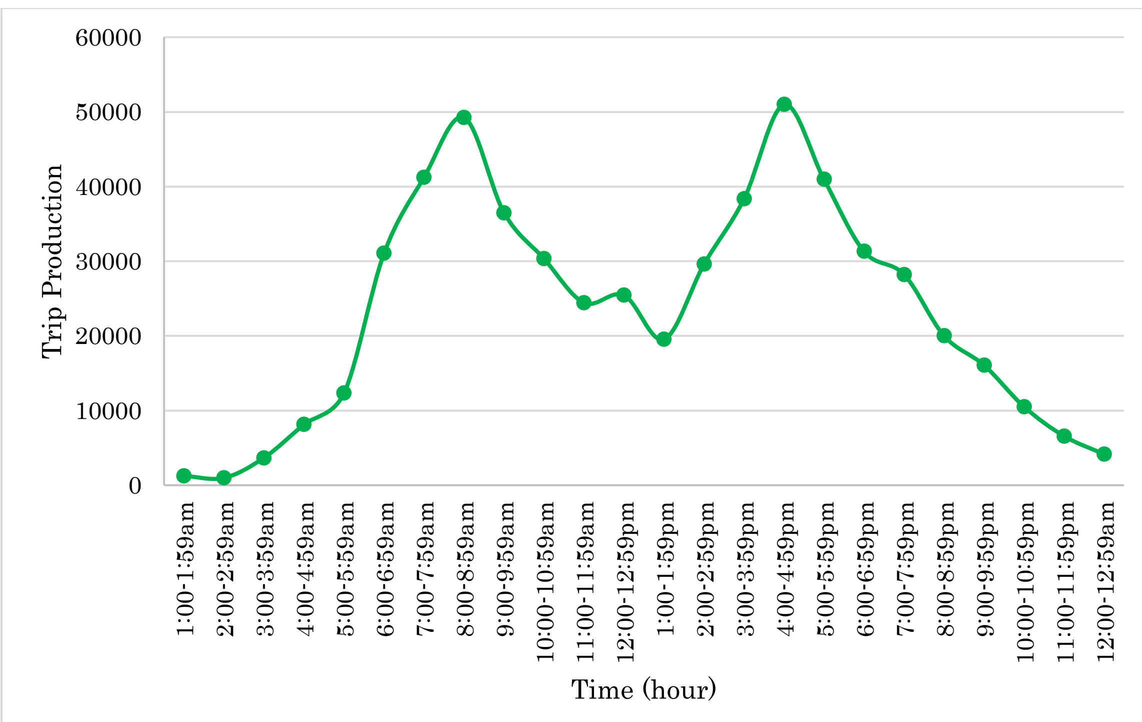


Figure 3-6 Hourly Passenger Car Flow Pattern

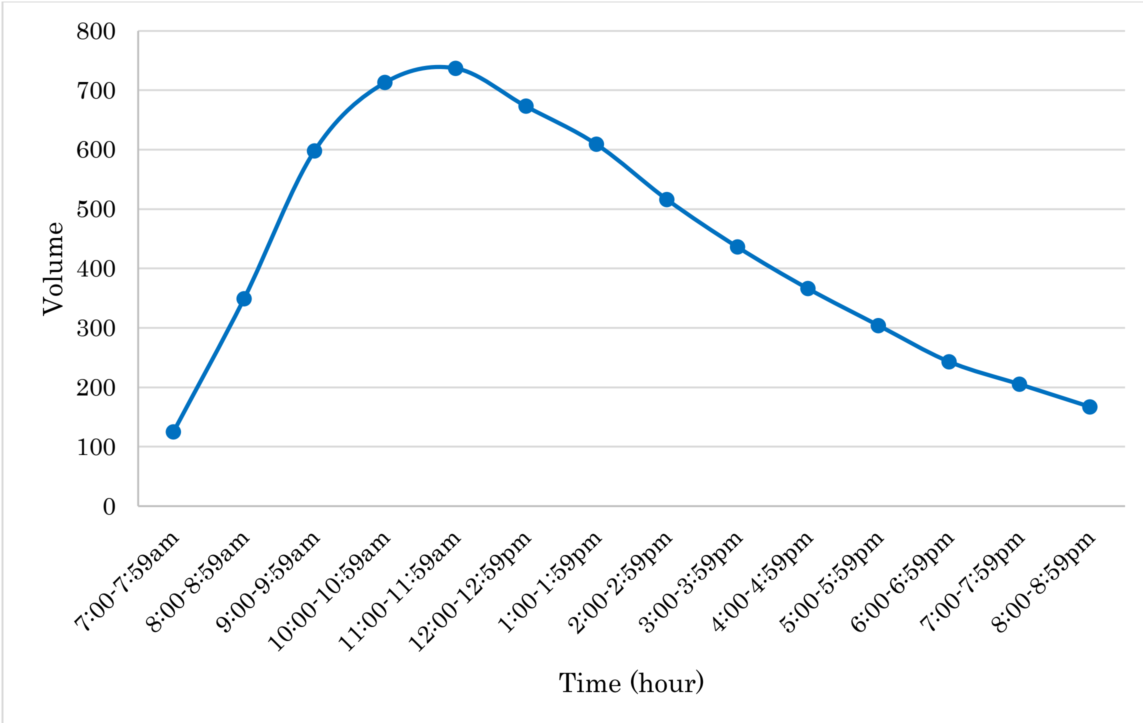


Figure 3-7 Hourly Long Haul Truck Flow Pattern

3.3.4 Multiclass Traffic Assignment

This study performs a standard multiclass traffic assignment, as described in the previous chapter (section 2.3.7), within the Halifax Regional Transport Network Model. The difference with earlier model is: earlier model considered truck mode for three peak periods (total six hour) only where, this model considers truck mode for a fourteen hour of period. Number of vehicles present within the network and number of iterations required to complete each hour of assignment is listed in Table 3-8. It is evident that, link flow peaks during morning peak hour and evening peak hour; however, evening period is more critical. In evening peak time maximum number of vehicles is present in the network and it takes relatively more iteration to reach the equilibrium condition of the network.

Table 3-8 Number of Iterations Required and Number of Vehicle Present Within the Network during Each Hour of Multiclass Traffic Assignment

Time period	Iteration required	Total Link flows in the Network	Time period	Iteration required	Total link flows in the Network
12:00-12:59am	2	176,809	12:00-12:59pm	3	1,446,762
1:00-1:59am	2	49,183	1:00-1:59pm	2	1,104,616
2:00-2:59am	2	38,414	2:00-2:59pm	5	1,650,572
3:00-3:59am	2	153,019	3:00-3:59pm	7	2,127,650
4:00-4:59am	2	374,356	**4:00-4:59pm**	**16**	**2,833,918**
5:00-5:59am	2	595,560	5:00-5:59pm	8	2,253,406
6:00-6:59am	5	1,617,252	6:00-6:59pm	5	1,695,375
7:00-7:59am	9	2,202,894	7:00-7:59pm	4	1,514,299
8:00-8:59am	**13**	**2,696,709**	8:00-8:59pm	2	1,049,716
9:00-9:59am	7	2,024,684	9:00-9:59pm	2	802,202
10:00-10:59am	5	1,707,933	10:00-10:59pm	2	502,292
11:00-11:59am	3	1,391,646	11:00-11:59pm	2	295,901

3.3.5 Calibration and Validation of the Model

Similar traffic volume-based approach that is adopted in previous chapter (section 0) is used to calibrate and validate the enhanced travel demand forecasting model developed in this chapter. The simulated and observed passenger car and truck counts are compared and the deviation is evaluated in terms of R^2, RMSE and GEH values. Certain links are imposed extra cost to discourage additional car and truck flows than expected across those links. R^2 values are obtained utilizing regression curve, and RMSE and GEH values are estimated using equations 13 and 14 from previous chapter. In total nine locations (Figure 2-11 of previous chapter) are validated with six hours (two hours of each morning, mid-day and evening peak period) of observed field traffic count data. For this model passenger car volume and truck volumes are validated separately. The validation results for both passenger car and truck movements are shown in Table 3-9.

Table 3-9 Validation Results of Enhanced Travel Demand Model

Criteria	Time		Goodness fit of the Model	
			Passenger Car Volume	Truck Volume
R^2	Morning Peak (7:00-8:59am)		0.94	0.84
	Mid-day Peak (11:00am-12:59pm)		0.84	0.89
	Evening Peak (4:00-5:59pm)		0.86	0.86
RMSE	Morning Peak (7:00-8:59am)		218.1	15.98
	Mid-day Peak (11:00am-12:59pm)		235.9	19.29
	Evening Peak (4:00-5:59pm)		323.2	20.98
GEH	Morning Peak (7:00-8:59am)	GEH < 1	44.59%	37.50%
		1 < GEH < 2	14.86%	16.67%
		2 < GEH < 5	17.57%	33.33%
		5 < GEH < 10	22.97%	12.50%
	Mid-day Peak (11:00am-12:59pm)	GEH < 1	39.19%	29.17%
		1 < GEH < 2	24.32%	29.17%
		2 < GEH < 5	18.92%	37.50%
		5 < GEH < 10	17.57%	4.17%
	Evening Peak (4:00-5:59pm)	GEH < 1	45.95%	33.33%
		1 < GEH < 2	18.92%	4.17%
		2 < GEH < 5	14.86%	50.00%
		5 < GEH < 10	20.27%	12.50%

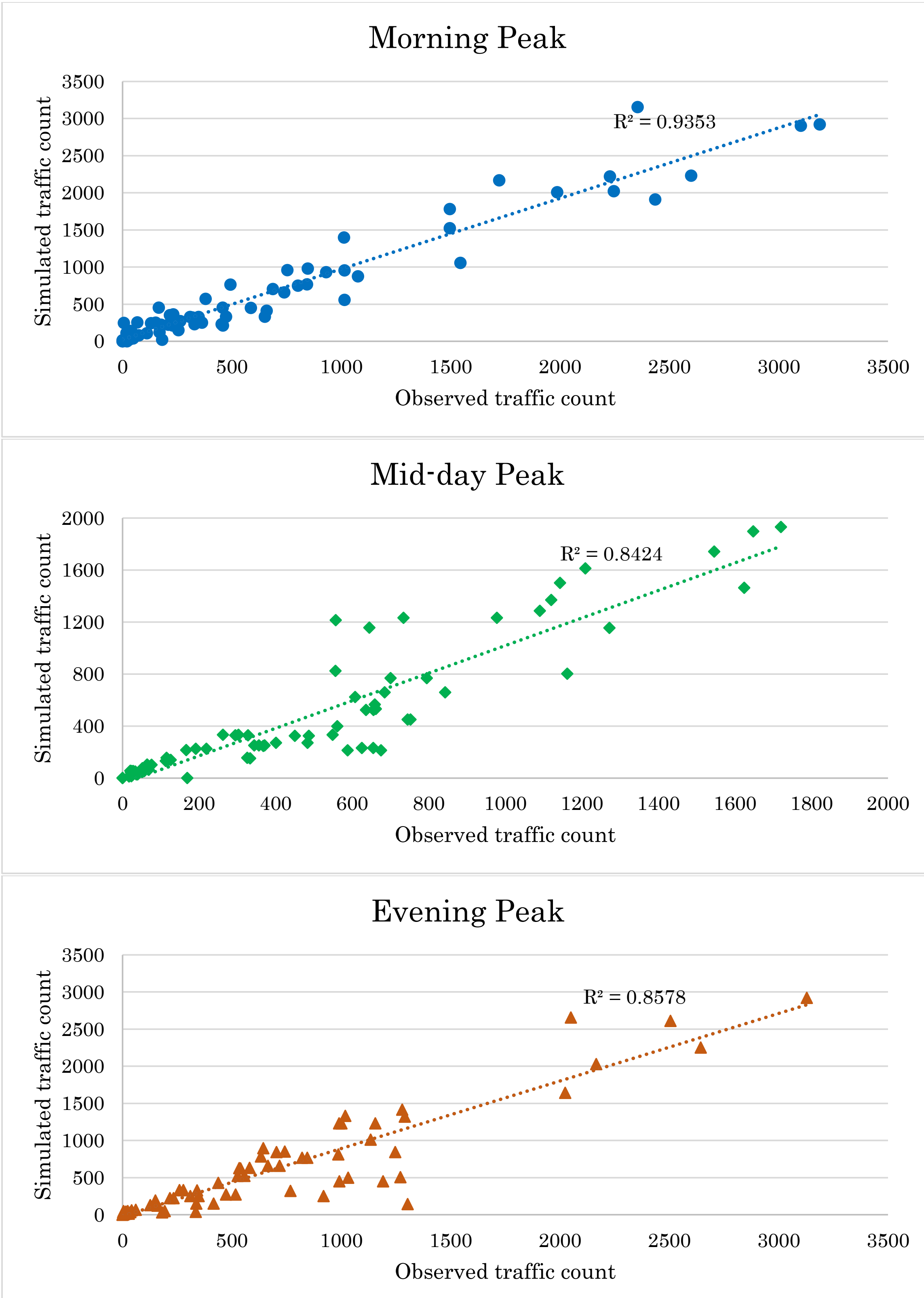


Figure 3-8 Comparison of Observed and Simulated Passenger Car Count

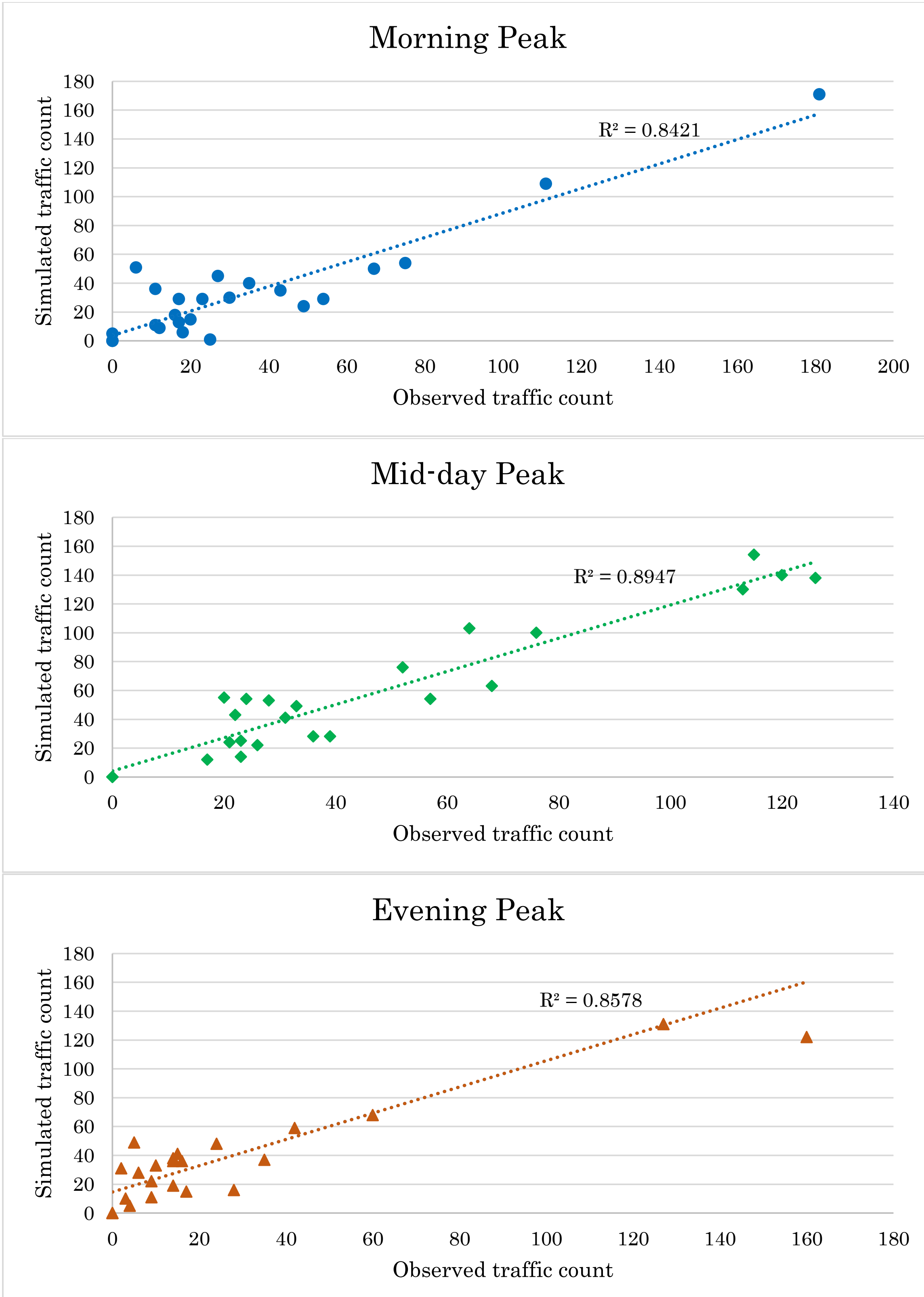


Figure 3-9 Comparison of Observed and Simulated Truck Count

The R^2 for three periods (morning, mid-day and evening peak period) are found as (Figure 3-8 and Figure 3-9) 40.94, 0.84 and 0.86 for passenger car and 0.84, 0.89, and 0.86 for truck movements respectively. RMSE estimates the absolute deviation of the simulated and observed traffic volume. The average RMSE values for three periods are found as 218.1, 235.9 and 323.2 for passenger cars and 15.98, 19.29, and 20.98 for truck movements respectively. GEH values are also evaluated for the flows of these modes. In the case of passenger car, GEH values of less than 1 has been found for 44.59%, 39.19%, and 45.95% of passenger car movement at three peak periods respectively and less than 5 for 77.03%, 82.43%, and 79.73% of total passenger car movement. On the other hand, for truck flows, GEH values of less than 1 has been found for 37.5%, 29.17%, and 33.33% of traffic movement at three peak periods respectively and less than 5 for 87.5%, 95.83%, and 87.5% of total traffic movement. No movement has a GEH value greater than 10.

3.4 Results and Discussion

3.4.1 Results of Overall Trip Generation and Distribution

Figure 3-10 presents daily trip (tour leg for delivery trucks) generation of different vehicles at TAZ level. The total trip generation comprises of 94.6% passenger car and 5.45% truck trips. Downtown Halifax and Dartmouth generate a significant number of trips. Generation of passenger car trips is higher in urban and sub urban areas. The results suggest that truck generation is concentrated in urban core, including port, airport, container terminals, intermodal terminal, and industrial areas located in Burnside and Bayers lake areas. In comparison to earlier trip-based model, this enhanced model estimates 3.3% and 12.1% higher passenger car and truck generation respectively.

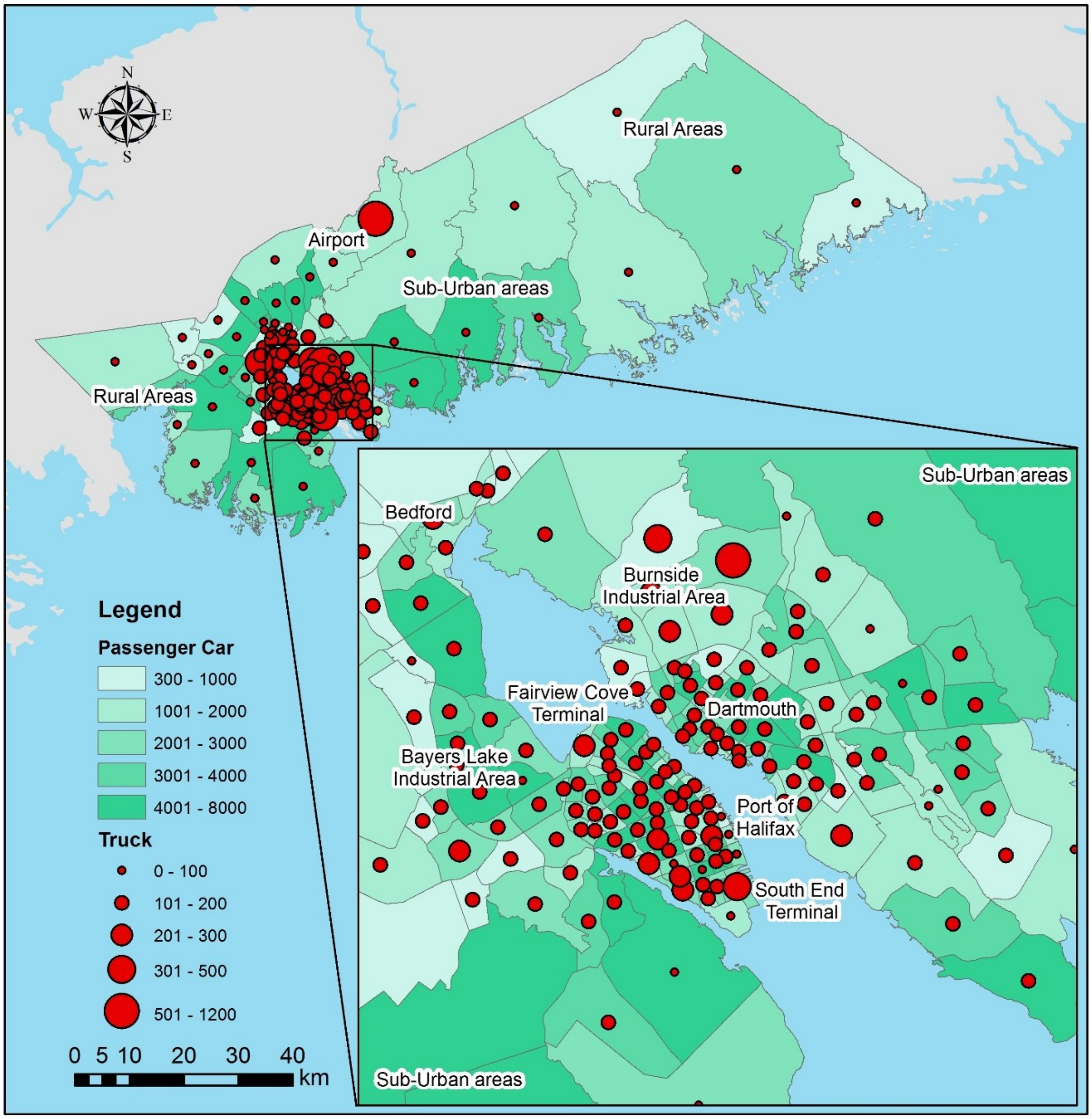


Figure 3-10 Daily Trip (or Tour Leg) Generation at Different TAZs

3.4.2 Results of Multiclass Traffic Assignment

Halifax Regional Transport Network Model includes movement of passenger cars, local delivery trucks and long haul trucks. The result of multiclass traffic assignment provides hourly link-volume for all modes as shown in Figure 3-11. Figure shows the flows of three modes with three different colors where thicker to thin line represents low to high traffic volume respectively.

Figure 3-11 Result of Multiclass Traffic Assignment

This result reveals that the two bridges anticipate the maximum flow in the network. Passenger car comprises the major portion the traffic flows in Halifax. In the case of truck flows, 52.29% of total delivery truck movement and 12.5% of total long haul truck movements occurs within the urban core. 64.6% of long haul truck movement occurs through Truro (external TAZ). Arguably, this external TAZ links Halifax with other parts of Canada.

For a better understanding of the overall multiclass traffic assignment performance, Table 3-10 presents hourly Vehicle Hour Travelled (VHT), Vehicle Kilometer Travelled (VKT), and average speed. The results show that, passenger car and truck flow is significantly high from 3:00pm to 5:59pm with a peak between 4:00pm and 4:59am. The number of passenger car is higher from 8:00am to 8:59am during morning commuting time, and the lowest during 2:00am to 2:59am. In contrast, commercial vehicle movement is the maximum during mid-day period and minimum in the morning time. Number of delivery truck ranges from a minimum value of 540 (from 7:00am to 7:59am) to a maximum value of 3,172 (from 11:00am to 11:59am). Similarly, number of long haul truck ranges from 125 (from 7:00am to 7:59am) to 737 (from 11:00am to 11:59am). VKT, and VHT also follow the same trend for both passenger car and truck. For instance, VKT of passenger car ranges from 14,830 (from 2:00am to 2:59am) to 922,431 (from 4:00pm to 4:59pm) and VKT of delivery truck ranges from 3,197 (from 11:00am to 11:59am) to 21,561 (from 7:00pm to 7:59pm). Average speed of passenger car ranges from 66.64km/h to 70.2km/h within the network. Average speed profile for all three modes is presented in Appendix G (Figure G-1). The speed profile shows a reverse pattern compared to passenger car volume profile in Figure 3-6 which establishes a reciprocal relationship between volume and speed.

Table 3-10 Summary of Multiclass Traffic Assignment Results

Time	Mode	Vehicle Volume	Vehicle Hours Travelled	Vehicle Km Travelled	Average Speed (Km/H)
12:00-12:59am	Passenger Car	4,132	227,372	65,468	69.92
1:00-1:59am	Passenger Car	1,224	66,367	19,063	70.16
2:00-2:59am	**Passenger Car**	**960**	**51,581**	**14,830**	**70.20**
3:00-3:59am	Passenger Car	3,656	198,754	57,248	70.08
4:00-4:59am	Passenger Car	8,124	459,478	132,695	69.91
5:00-5:59am	Passenger Car	12,326	715,036	206,790	69.84
6:00-6:59am	Passenger Car	31,059	1,932,812	547,561	68.51
7:00-7:59am	Passenger Car	41,244	2,672,640	737,021	67.75
	Delivery Truck	**540**	**11,457**	**3,197**	**71.54**
	Long Haul Truck	**125**	**25,347**	**9,357**	**84.12**
8:00-8:59am	Passenger Car	49,266	3,314,739	888,709	67.04
	Delivery Truck	1500	35,975	9,452	70.30
	Long Haul Truck	349	70,166	25,750	76.73
9:00-9:59am	Passenger Car	36,493	2,324,568	648,562	67.09
	Delivery Truck	2589	61,474	17,301	71.79
	Long Haul Truck	598	117,352	43,289	78.42
10:00-10:59am	Passenger Car	30,334	1,889,838	534,098	68.48
	Delivery Truck	3060	74,265	21,276	72.45
	Long Haul Truck	713	139,294	51,439	79.87
11:00-11:59am	Passenger Car	24,435	1,487,552	425,197	68.97
	Delivery Truck	**3172**	**74,436**	**21,561**	**72.65**
	Long Haul Truck	**737**	**143,837**	**53,207**	**80.15**
12:00-12:59pm	Passenger Car	25,437	1,560,777	444,521	68.89
	Delivery Truck	2892	69,740	20,246	72.16
	Long Haul Truck	673	131,014	48,495	80.02
1:00-1:59pm	Passenger Car	19,530	1,172,738	336,890	69.31
	Delivery Truck	2580	60,988	17,890	72.67
	Long Haul Truck	609	118,441	43,880	80.39
2:00-2:59pm	Passenger Car	29,601	1,845,987	522,076	68.52
	Delivery Truck	2243	54,439	15,798	72.02
	Long Haul Truck	516	101,403	37,499	79.90
3:00-3:59pm	Passenger Car	38,353	2,473,017	685,882	67.87
	Delivery Truck	1879	45,980	12,870	71.46
	Long Haul Truck	436	86,654	31,951	77.89
4:00-4:59pm	**Passenger Car**	**50,998**	**3,481,880**	**922,431**	**66.64**
	Delivery Truck	1574	39,556	10,317	69.81
	Long Haul Truck	366	73,452	26,921	76.24
5:00-5:59pm	Passenger Car	40,956	2,663,283	734,530	67.73
	Delivery Truck	1315	32,912	9,110	70.93
	Long Haul Truck	304	61,295	22,582	77.76
6:00-6:59pm	Passenger Car	31,314	1,961,125	553,454	68.43
	Delivery Truck	1044	25,261	7,222	72.14
	Long Haul Truck	243	48,323	17,875	80.70
7:00-7:59pm	Passenger Car	28,218	1,743,826	495,718	68.77

Time	Mode	Vehicle Volume	Vehicle Hours Travelled	Vehicle Km Travelled	Average Speed (Km/H)
	Delivery Truck	880	21,106	6,119	72.12
	Long Haul Truck	205	41,478	15,359	80.92
8:00-8:59pm	Passenger Car	20,004	1,202,463	345,603	69.33
	Delivery Truck	710	16,261	4,770	72.16
	Long Haul Truck	167	33,808	12,536	81.68
9:00-9:59pm	Passenger Car	**16,064**	951,368	274,302	69.53
10:00-10:59pm	Passenger Car	10,498	607,326	175,283	69.81
11:00-11:59pm	Passenger Car	**6,559**	367,229	105,775	69.97

3.4.3 Results of Delivery Truck Tour Model

This study presents results obtained from the tour-based delivery truck movement model and multiclass traffic assignment. The delivery truck tour model generates spatial and temporal distribution of truck tour production in the Halifax Transport Network Model. To achieve a better understanding of local congestion, the obtained delivery truck tours are assigned within the simulation model and link truck flows are generated at different time of the day. The results obtained from this study are discussed separately in the following sections.

3.4.3.1 *Spatial Variation of Truck Tour Production*

Figure 3-12 shows spatial variation of local delivery truck tour production under each establishment type. Result shows that urban zones are major generator of local delivery truck tours followed by suburban and rural zones. The results of delivery truck model show that, service sector generates the highest number of delivery truck tour from different TAZs in the network, followed by retail and industry sector. Maximum delivery truck tours are generated from urban and suburban areas for almost all establishment types. Wholesale contributed the least to truck tour generations. However, Wholesale generated a relatively higher number of tours at suburban areas with respect to those in urban areas as most of the industries are located in suburban areas. Results also reveal that there is a large concentration of commercial vehicle movement around the port, airport, and industrial areas.

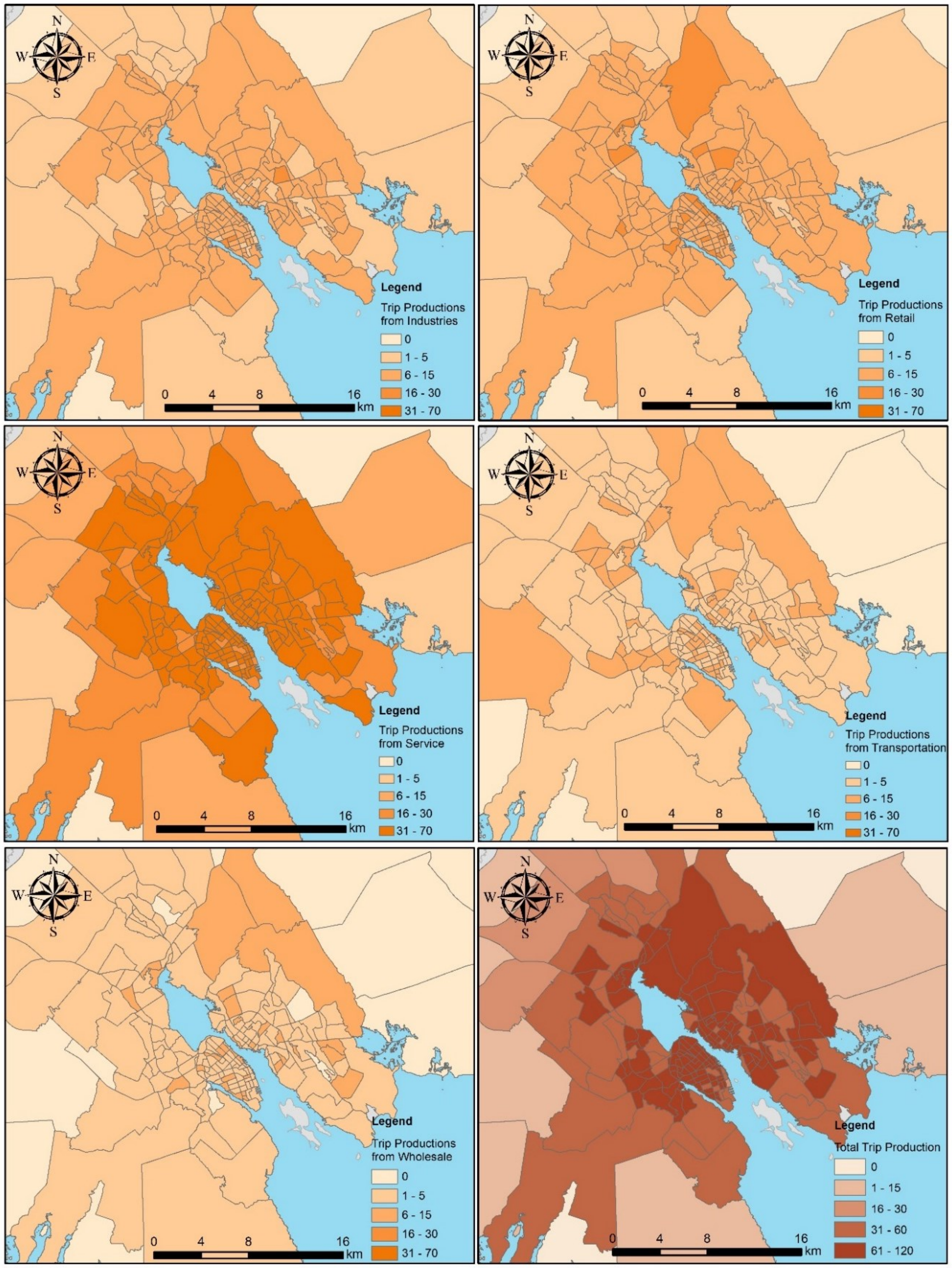


Figure 3-12 Daily Tour Production from Different Establishment Type

3.4.3.2 *Temporal Variation of Truck Tour Production*

This study examines temporal variations of commercial vehicle tour legs (trips) production for the duration of 7:00am to 8:59pm (Figure 3-13). The results reveal that the maximum number of trucks are present in the network in the hour of 11:00-11:59am. Service is found to generate a higher trip production for all times of the day. Almost all other establishments follow a similar temporal pattern for the generation of truck trips. Majority of the tours were generated in first three hours by 17%, 30%, and 34% respectively. The return of trucks to their origination location is distributed more evenly for a nine-hour period starting from 12:00pm to 9:00pm which ranges 7% to 15%.

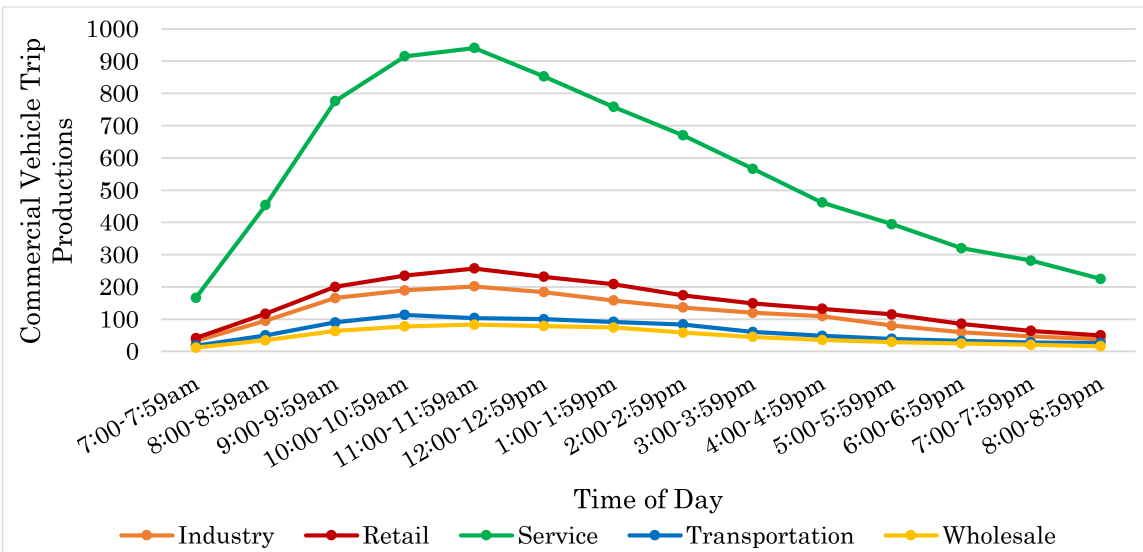


Figure 3-13 Daily Commercial Vehicle Trip (Tour Leg) Productions in Halifax

3.4.3.3 *Network Performance of Delivery Trucks*

Figure 3-14 shows the total daily link volume of delivery trucks. It is evident that the road network in the urban core of Halifax experiences higher delivery truck flow, which is represented by thicker lines in the following schematic. 43.9% of total delivery trucks movement occurs in this region. This figure also shows that Highway 102, the major arterial corridor of Barrington Street and the Mackay Bridge facilitates most delivery truck movement.

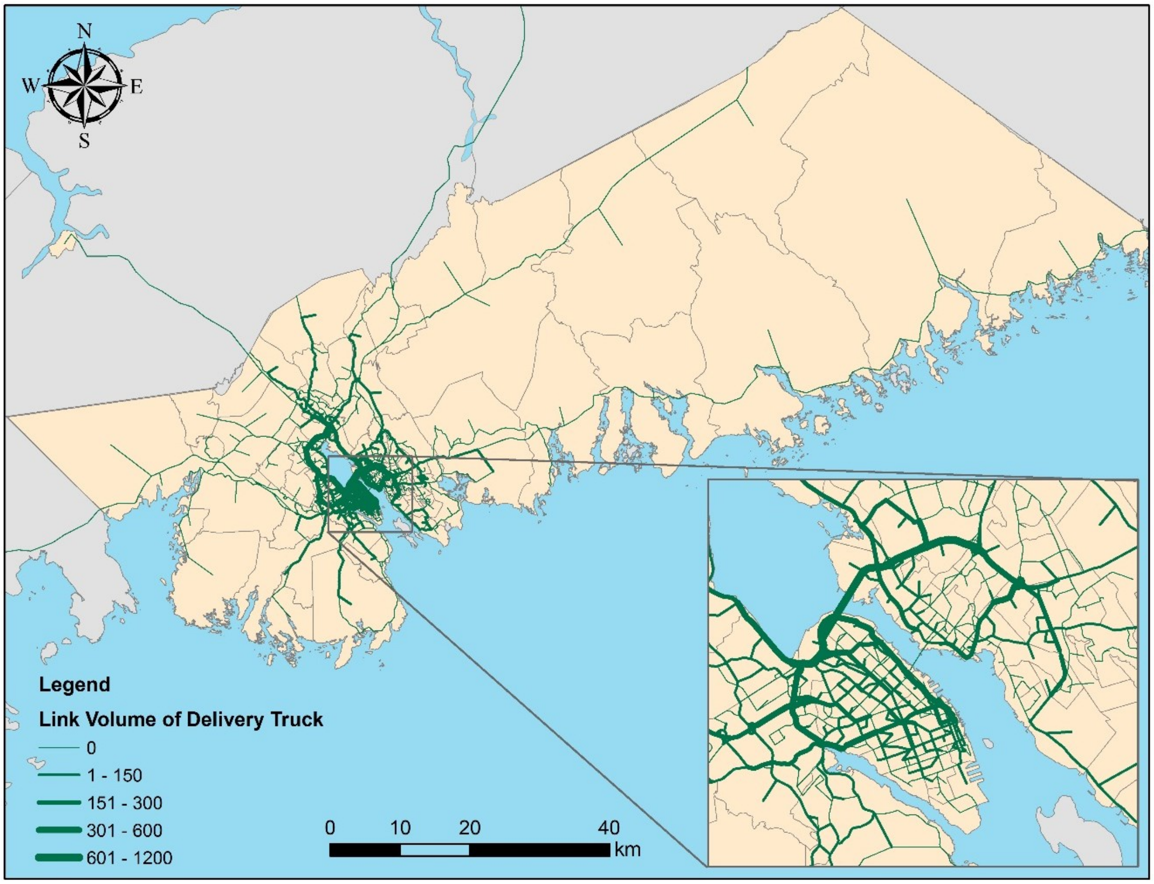


Figure 3-14 Daily Total Link Volume of Delivery Trucks

This study also reports different tour attributes including length of tour legs, leg travel time and link truck volume for each hour of tour operation. Table 3-11 presents minimum, quartiles, maximum and average values of the attributes. The results suggest that the average length of tour leg ranges between 6.99km to 7.32km with a minimum value of 0.31km and a maximum of 34.55km. The average travel time of truck trips range from 28.07 minutes to 33.01 minutes, the average number of delivery truck across links varies from 6 to 20 and the maximum link truck flow is 66. Maximum link truck flow occurs during mid-day (12:00-12:59pm) across Barrington Street which is one of the major connecting links between port and local destinations. Moreover, the maximum length of tour legs is found in the morning from 7:00am to 7:59am.

Table 3-11 Network Performance for Delivery Truck Tour

Time Interval	Attribute	Minimum	25 Percentile	Average	75 Percentile	Maximum
7:00-7:59am	Length of tour leg (km)	0.68	3.80	7.10	9.75	34.55
	Travel time of tour leg (min)	0.81	16.39	30.74	46.84	59.45
	Link truck flow	1	2	6	7	50
8:00-8:59am	Length of tour leg (km)	0.43	3.99	7.35	10.43	25.71
	Travel time of tour leg (min)	0.86	14.25	28.07	42.64	59.45
	Link truck flow	1	3	9	13	33
9:00-9:59am	Length of tour leg (km)	0.37	3.88	7.13	10.19	29.10
	Travel time of tour leg (min)	0.56	18.33	31.51	44.77	59.99
	Link truck flow	1	5	12	18	40
10:00-10:59am	Length of tour leg (km)	0.42	3.86	7.10	10.09	29.10
	Travel time of tour leg (min)	0.23	16.81	31.13	47.26	59.86
	Link truck flow	1	6	16	23	54
11:00-11:59am	Length of tour leg (km)	0.31	3.86	6.99	9.99	25.32
	Travel time of tour leg (min)	0.30	16.16	31.03	46.46	59.71
	Link truck flow	1	7	19	28	61
12:00-12:59pm	Length of tour leg (km)	0.37	3.89	7.07	9.92	34.54
	Travel time of tour leg (min)	1.00	18.87	32.07	46.57	59.79
	Link truck flow	1	7	20	28	66
1:00-1:59pm	Length of tour leg (km)	0.32	3.86	7.07	10.06	22.79
	Travel time of tour leg (min)	0.93	14.50	30.92	49.02	59.89
	Link truck flow	1	6	14	21	48
2:00-2:59pm	Length of tour leg (km)	0.35	3.81	7.10	10.06	29.10
	Travel time of tour leg (min)	0.14	17.27	30.59	44.72	59.92
	Link truck flow	1	5	13	19	47
3:00-3:59pm	Length of tour leg (km)	0.41	3.95	7.05	9.88	17.22
	Travel time of tour leg (min)	0.21	16.09	31.99	47.90	59.32
	Link truck flow	1	4	13	18	42
4:00-4:59pm	Length of tour leg (km)	0.43	3.79	7.00	10.03	25.33
	Travel time of tour leg (min)	0.78	13.96	28.60	42.55	59.75
	Link truck flow	1	4	10	14	36
5:00-5:59pm	Length of tour leg (km)	0.43	3.85	7.04	10.00	25.22
	Travel time of tour leg (min)	0.99	13.98	28.29	41.75	59.65
	Link truck flow	1	3	9	13	30
6:00-6:59pm	Length of tour leg (km)	0.61	3.98	7.15	10.22	17.64
	Travel time of tour leg (min)	1.98	19.60	33.01	43.95	57.71
	Link truck flow	1	3	8	11	27
7:00-7:59pm	Length of tour leg (km)	0.41	3.86	7.03	9.91	25.26
	Travel time of tour leg (min)	1.42	18.56	32.82	47.56	59.99
	Link truck flow	1	3	7	11	25
8:00-8:59pm	Length of tour leg (km)	0.48	3.99	7.32	10.58	24.80
	Travel time of tour leg (min)	0.85	18.68	32.65	46.81	59.88
	Link truck flow	1	2	9	12	56

3.5 Conclusion

This study develops an enhanced travel demand forecasting model that includes a trip-based passenger car movement and a tour-based delivery truck movement to perform a multiclass traffic assignment within the Halifax transport network. A NovaTRAC travel activity survey is used to inform passenger car demand modeling with 24-hour travel log information. A novel approach of Monte Carlo simulation technique is proposed by utilizing a rich firm-level data source. The model was extensively calibrated and validated using video image processing-based traffic count data sources. This study offers a better understanding of the spatial and temporal distribution of commercial vehicle movement in combination with passenger cars in Halifax.

Passenger car flows is maximum during evening peak period. Solely downtown core experiences 45.53% of total daily car flows. In comparison, sub urban area anticipates 38.6% of total car flows. In the case of truck flows, urban and suburban are likely to experience equal truck flow. The result of tour-based truck delivery model reports that Service sector generates highest delivery truck tour, followed by Retail, and Industry among all establishment types. Wholesale generates relatively lower number of tours compared to other establishment types. Average link flow of hourly delivery truck movement ranges from 6 to 20 and this flow peaks at mid-day period. The results indicate that firms are likely to complete their deliveries in between morning and evening peak periods. The assignment results suggest that the average length of tour leg ranges between 6.99km to 7.32km with a minimum value of 0.31km and a maximum of 34.55km. The anticipated commercial vehicle flow results will be useful to determine the dimensions of the infrastructure on and around industrial sites that are being planned. This research will offer better integration of spatial and traffic planning by providing information about the effects of industrial activities on transport and traffic in early stages of the planning process of industrial areas.

Nevertheless, an inclusion of a local truck delivery system within the regional transport network modeling has increased the performance of the model reasonably better compared to the earlier models *(Bela and Habib, 2018a; Bela and Habib, 2018b)* as it accumulates intra-urban and inter-urban truck flows. Such improvement of the model is essential for policy analysis regarding the estimation of Greenhouse Gas (GHG) and other vehicular emission. Particularly the Federal Government of Canada has adopted a carbon trade policy which requires a comprehensive urban freight network modeling framework to consider all modes to better forecast truck flows and mixed traffic conditions in a congested urban transport network. Without such model, it could be difficult to develop market mechanics and policies for carbon trade policy. A comprehensive urban freight network modeling framework tool will be useful to test different policy scenarios that ensures environment sustainability.

Chapter 4

Emission Modelling[3]

4.1 Introduction

Greenhouse gas (GHG) emissions are a growing concern for personal health and the environment *(Sivanandan et al., 2008)*. Vehicular traffic emissions significantly contribute to air pollution which further leads to pollution related health risks, such as lung cancer, developing asthma or other respiratory diseases, Chronic Obstructive Pulmonary Disease, cardiovascular disease, and could lead to premature death *(Andersen et al., 2011; McConnell et al., 2010; COMEAP, 2010; Beelen et al., 2008; Laden et al., 2006; Kim et al., 2004; Abbey et al, 1999)*. In Canada, vehicular traffic emissions are responsible for 25% of its total emissions *(COMEAP, 2010)*. Particularly, freight transport is a major concern when trucks move through highly populated urban areas and contribute to the air quality degradation *(Künzli et al., 2000)*. This poses serious public health threats and raises the severity of related illnesses *(Künzli et al., 2000)*. The large vehicle flow of the Halifax Regional Municipality significantly contributes to the air pollution challenges of this city. Interestingly, there is no current traffic emission model for this region that considers commercial vehicle in combination with passenger cars. According to

[3] This chapter is largely derived from the following peer-reviewed conference papers,

Bela, P. L., and Habib, M. A. (2018b). "Urban Freight Network and Emission Modelling for Port City Halifax, Canada: A Spatial and Temporal Evaluation of Commercial Vehicles Movement". *Proceedings of the 97th Annual Meeting of Transportation Research Board*, *Washington, D. C.,* January 7-11, (No. 18-06689) and

Bela, P. L. and Habib, M. A. (2018a) "Development of a Freight Traffic Model for Halifax, Canada". *Proceedings of the 53rd Conference of Canadian Transportation Research Forum (CTRF)*, Toronto, Canada, pp. 82-89 a study, commercial vehicles can contribute up to 38% of transportation's GHG emissions in USA *(US Environmental Protection Agency, 2003).* Therefore, traffic emission modeling, with consideration of commercial vehicles contribution to emissions, in combination with other modes is of paramount importance, especially for this region of Nova Scotia. To do so, a multiclass traffic network modelling is pre-requisite to assess emission from all types of vehicles.

Therefore, the objectives of this chapter are (i) to develop an emission modelling framework for HRM to estimate the disaggregated emission of major pollutants (ii) to develop regional level inventories from different data sources including the travel demand models developed for Halifax to feed the emission model. This chapter integrates the multiclass traffic network model developed within the Equilibre Multimodal Multimodal Equilibrium (EMME) platform with an emission modelling framework based on Motor Vehicle Emission Simulator (MOVES), developed by the US Environmental Protection Agency (USEPA). The first model provides the emission model with necessary inventories (i.e. VKT, speed distribution, vehicle type fraction) for estimating the emission of major pollutants: GHG (as CO_2-equivalent), carbon monoxide (CO), nitrogen oxides (NOx), sulphur dioxide (SO_2), particulate matter ranging from 2.5 μm to 10 μm (PM_{10}), particulate matter smaller than 2.5 μm ($PM_{2.5}$), total hydrocarbons (THC), and volatile organic compounds (VOC) in traffic analysis zones (TAZs) level for the HRM.

4.2 Literature Review

Air quality degradation is one of the most pressing environmental concerns worldwide, particularly in North American cities *(Abou-Senna and Radwan, 2014b).* Vehicular emissions contribute significantly in the deterioration of the climate that adversely affects social, economic, environmental and public health worldwide. Many studies assessed the emission rate of a specified area within a set of time period, to capture the temporal variation of a variety of pollutants *(Abou-Senna and Radwan, 2014a, Abou-Senna and Radwan, 2014b, Sider et al., 2013; Farzaneh and Zietsman, 2012; Choi and Frey, 2010; Frey et al., 2008; Hatzopoulou et al., 2008; Sivanandan et al., 2008)*. According to several studies, the major air pollutants include CO_2, CO, NOx, SO_2, PM_{10}, $PM_{2.5}$, THC and VOC *(Sivanandan et al., 2008; Abou-Senna and Radwan, 2014b, Sider et al., 2013; Farzaneh and Zietsman, 2012; Maoh and Tang, 2012; Environment Canada, 2014; Choi and Frey, 2010; Frey et al., 2008; Potoglou and Kanaroglou, 2008; Behan et al., 2008; US Environmental Protection Agency, 2005; Gajendran and Clark, 2003).* Among these pollutants, EPA sets National Ambient Air Quality Standards (NAAQS) for CO, NOx, SO_2, and PMs which are defined as Criteria Air Contaminant (CAC).

The transportation sector in Canada contributes to almost one quarter (24% in 2012) of the overall greenhouse gas emissions for the country, and over half of the CO_2 emissions are produced by fossil fuel powered vehicles *(Environment Canada, 2014; Behan et al., 2008).* Vehicle engines produce high amounts of air pollution due to incomplete combustion of the fuel gases which are released into the air through the exhaust fumes *(Behan et al., 2008)*. Automobile exhaust fumes expend greenhouse gas emissions such as CO_2, CO, NOx, and HC, along with PM *(Potoglou and Kanaroglou, 2008)*. Due to never ending sprawl, an increased volume of single occupant vehicles for commuting is causing increased air pollution *(Maoh and Tang, 2012)*. Emissions from this sector increased by 31% between 1990 and 2005, making the transportation sector the second largest contributor to GHG emissions in Canada *(Environment Canada, 2014).* For these reasons the current transportation system, where the majority of the population relies on commuting alone in a personal vehicle, has been deemed unsustainable *(Egbue and Long, 2012).* Wang et al. *(2013)* estimated that CO_2 emissions are lower for households in mixed land use neighborhoods with denser road networks and better network connection. As expected, the highest amounts of GHG emissions are found close to roadways, therefore people living in cities are at higher risk of adverse effects *(Environment Canada, 2014; Hankey and Marshall, 2010)*. Recognizing the issues associated with vehicular emissions such as environmental degradation and individual health issues, governments have introduced stricter emission standards and vehicle inspection programs, among other steps to combat the negative effects *(HEI, 2010)*. Moreover, heavy duty diesel vehicles (HDDVs) contribute significantly to the emissions of NOx and PM *(Gajendran and Clark, 2003)*. According to a study conducted by USEPA, HDDVs are responsible for almost 46% and 54% of total NOx and PM emission respectively in United States *(US Environmental Protection Agency, 2005)*. The amount of emissions from these vehicles is affected by type of fuel used, driving cycle, vehicle class and weight of corresponding vehicle *(Brodrick et al., 2004; Clark et al., 2002)*. Sider et al. *(2013)* estimated NOx emission for Montreal and found that pollution along the main highway corridors and in the downtown areas is higher than other areas. Additionally, emissions are comparatively low for the peripheral zones.

In port cities, such as Halifax, trucks dominate the freight market due to their flexibility and cost characteristics relative to other modes. However, very often, the emission from commercial vehicle movement in the network, remains unaccounted. The emission modeling that accounts for truck movement is limited in literature. Irin and Habib *(2015)* estimated truck emissions for a Halifax corridor on one single truck route. Their study uses MOVES2010b platform for emission modeling of truck movement in Halifax for three different time periods. Although this corridor level studies are abundant in the existing literature, regional level transport network and emission models are limited. Therefore, this study aims to develop a comprehensive modelling framework for a multiclass travel demand forecasting and emission modelling. One of the unique contributions of this study includes a thorough investigation of spatial, temporal and zonal variation of major pollutants and criteria air contaminant in the port city Halifax by different vehicle types.

4.3 Modelling Approach

The emission model is developed within the latest version of USEPA's Motor Vehicle Emission Simulator (MOVES) platform. Emission modeling in MOVES2014a can be done in three basic analysis scales such as (i) Macro-scale analyses which are generally appropriate for developing large-scale (e.g., national) inventories (ii) Meso-scale analyses are suitable for developing local (i.e., county) inventories at a finer grained spatial and temporal resolution (iii) Micro-scale analyses estimate emissions for specific corridors and/or intersections, which is applicable for assessing the project-level performance *(US Environmental Protection Agency, 2009; US Environmental Protection Agency, 2015b).* This study performs county level emission analysis for the year of 2011 and 2016. Travel demand forecasting model for these two years that were developed in the previous two chapters are used to feed the different MOVES inventories along the process of emission modeling. For example, traffic volume, travel time, VKT and average speed are extracted from the travel demand models. Additionally, MOVES applies adjustment for weather, age of the vehicles and fuel for calculating the total emissions *(Vallamsundar and Lin, 2012; US Environmental Protection Agency, 2015a)*. Figure 4-1 shows the sequential steps of emission modeling within MOVES including the inputs, emission estimation and the outputs. MOVES uses an internal algorithm to estimate emission factor and total emission using the inputs obtained from multiple databases, and the regional models. A generic framework of emission estimation within MOVES is presented in Figure 4-2 *(Koupal et al., 2002).*

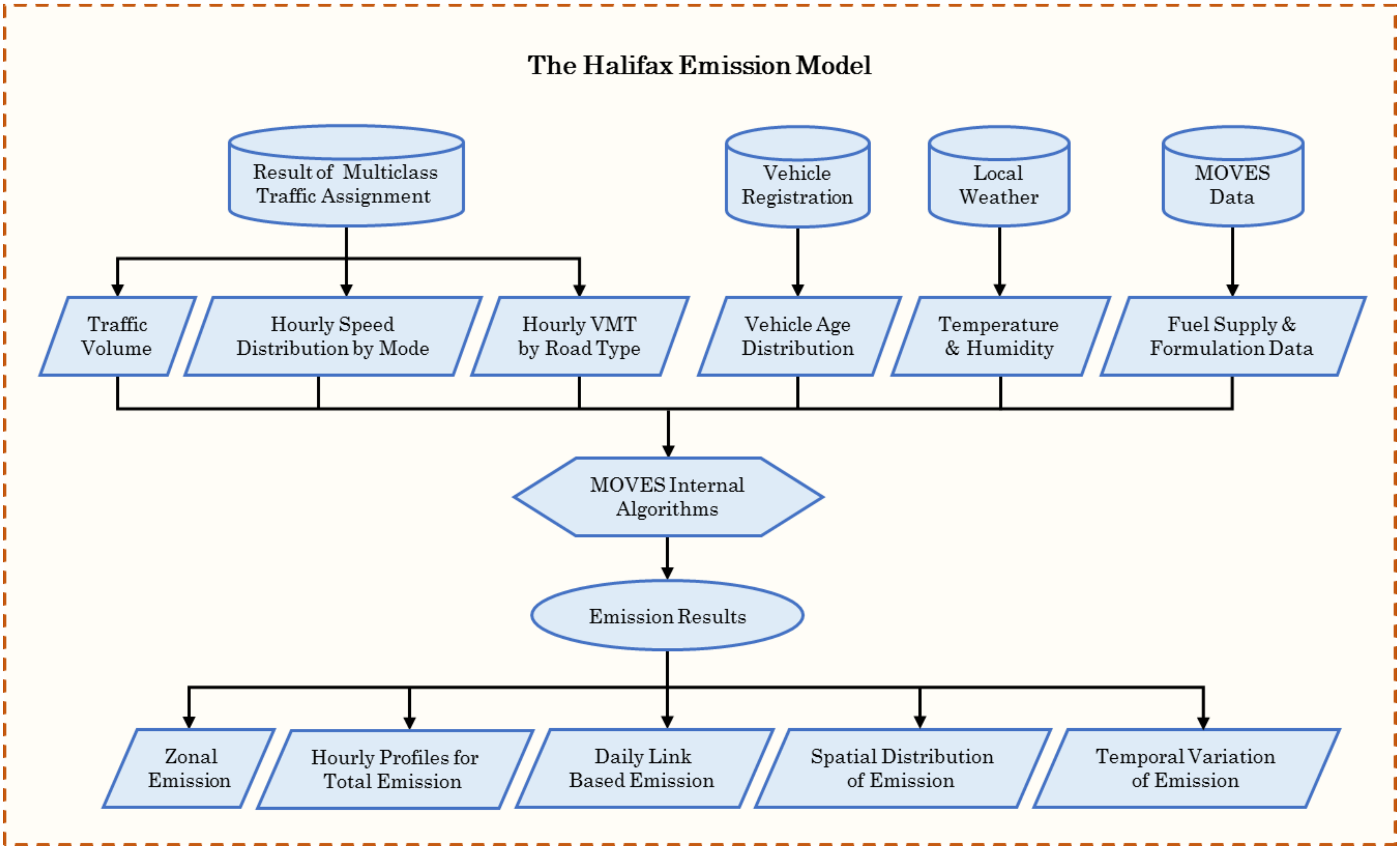


Figure 4-1 Framework for Emission Estimation from Multiclass Traffic Assignment

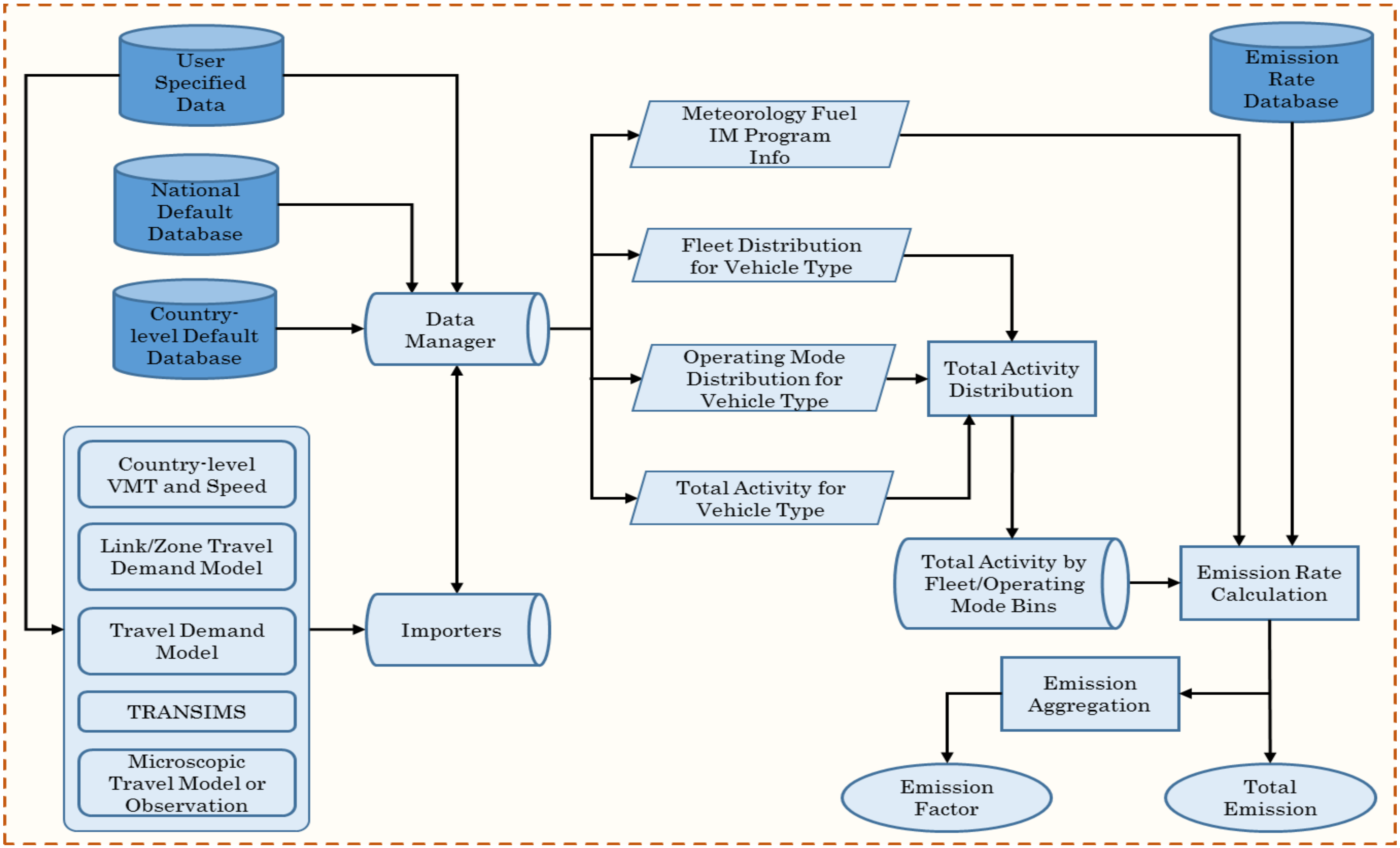


Figure 4-2 Generic Framework of MOVES Model

4.3.1 Methodology

The emission models for Halifax Regional Municipality (HRM) are developed within USEPA's Motor Vehicle Emission Simulator (MOVES) platform for two different model year (2011 and 2016). First model includes four modes i.e., passenger car, light truck, medium truck and heavy truck and the second model includes three modes i.e., passenger car, delivery truck and long haul truck. These two models are developed individually with their relevant attributes. These emission models are developed following three steps which include pre-processing, model execution and post-processing. Regional vehicular emission modelling requires a combination of data to reflect the local context, traffic characteristics, and traffic flow patterns of that area *(Koupal et al., 2002; US Environmental Protection Agency, 2015a)*. The pre-processing step includes the development of such inventories like: vehicle age distribution, vehicle type VMT distribution, road type distribution, source type population, average speed distribution, fuel and meteorological information to replicate the local context of Halifax. The inventories developed at this phase are used for creating a RunSpec to estimate different emission rates in the phase of model execution. Multiple data sources and multiclass traffic assignment results are used to develop these inventories. The vehicle age distribution fraction as shown in Table 4-1, is estimated from the vehicle registry database of Canadian Vehicle Survey 2015. This table informs vehicle age fraction for the last 30 years. The darker color represents the higher percentage and the lighter presents the lower percent values. The data reveals that majority of the passenger cars running on the road are the age of 13 years or less. For example, 85% of the passenger cars are the age of 13 years or less. In the case of commercial vehicles, majority are 15 years old or less. The Table shows that 81% of heavy trucks are 15 years old or less. The age of vehicle affects significantly to its emission as modern vehicles attempt to optimize combustion of fossil fuels *(Natural Resources Canada, 2018).*

Table 4-1 Vehicle Age Fraction by Vehicle Types

Vehicle model year	Passenger Car	Light Truck	Medium Truck	Heavy Truck
Current Year	0.49%	0.17%	0.65%	1.13%
1 year old	5.08%	2.60%	3.89%	5.17%
2 years old	8.55%	6.53%	6.31%	6.08%
3 years old	8.60%	6.18%	8.18%	10.17%
4 years old	7.19%	6.95%	7.10%	7.25%
5 years old	7.69%	5.70%	6.82%	7.95%
6 years old	6.93%	5.36%	5.66%	5.96%
7 years old	7.79%	5.42%	4.90%	4.37%
8 years old	7.45%	4.26%	3.71%	3.16%
9 years old	5.85%	4.14%	3.82%	3.51%
10 years old	6.49%	5.02%	5.76%	6.50%
11 years old	5.05%	5.42%	5.57%	5.72%
12 years old	4.89%	3.43%	4.07%	4.71%
13 years old	3.90%	3.31%	3.11%	2.91%
14 years old	2.56%	2.46%	2.73%	3.00%
15 years old	2.31%	3.73%	3.68%	3.63%
16 years old	1.84%	2.07%	2.27%	2.47%
17 years old	1.32%	2.02%	1.80%	1.57%
18 years old	1.11%	1.74%	1.37%	1.00%
19 years old	0.76%	1.88%	1.48%	1.08%
20 years old	0.38%	1.96%	1.56%	1.15%
21 years old	0.38%	1.96%	1.56%	1.15%
22 years old	0.38%	1.96%	1.56%	1.15%
23 years old	0.38%	1.96%	1.56%	1.15%
24 years old	0.38%	1.96%	1.56%	1.15%
25 years old	0.38%	1.96%	1.56%	1.15%
26 years old	0.38%	1.96%	1.56%	1.15%
27 years old	0.38%	1.96%	1.56%	1.15%
28 years old	0.38%	1.96%	1.56%	1.15%
29 years old	0.38%	1.96%	1.56%	1.15%
30 years old	0.38%	1.96%	1.56%	1.15%

Type of fuel used by each vehicle is determined from Nova Scotia Travel Activity (NovaTRAC) Survey 2016. Hourly meteorological data such as temperature and relative humidity (as shown in Figure 4-3) are obtained from the Halifax Naval Dockyard weather station (located on the western side of Halifax harbor and elevation is +3.8m) by Environment Canada *(Environment Canada, 2016)*. Hourly meteorological data is obtained for April 2011 and 2016. The traffic data used in this study is also collected at the same period. The

Figure shows that 31.82 F is recorded as the minimum temperature corresponding to a maximum relative humidity of 97% for a 24-hour period in the year of 2016. The data suggests that the temperature, and the relative humidity exhibit an inverse relationship.

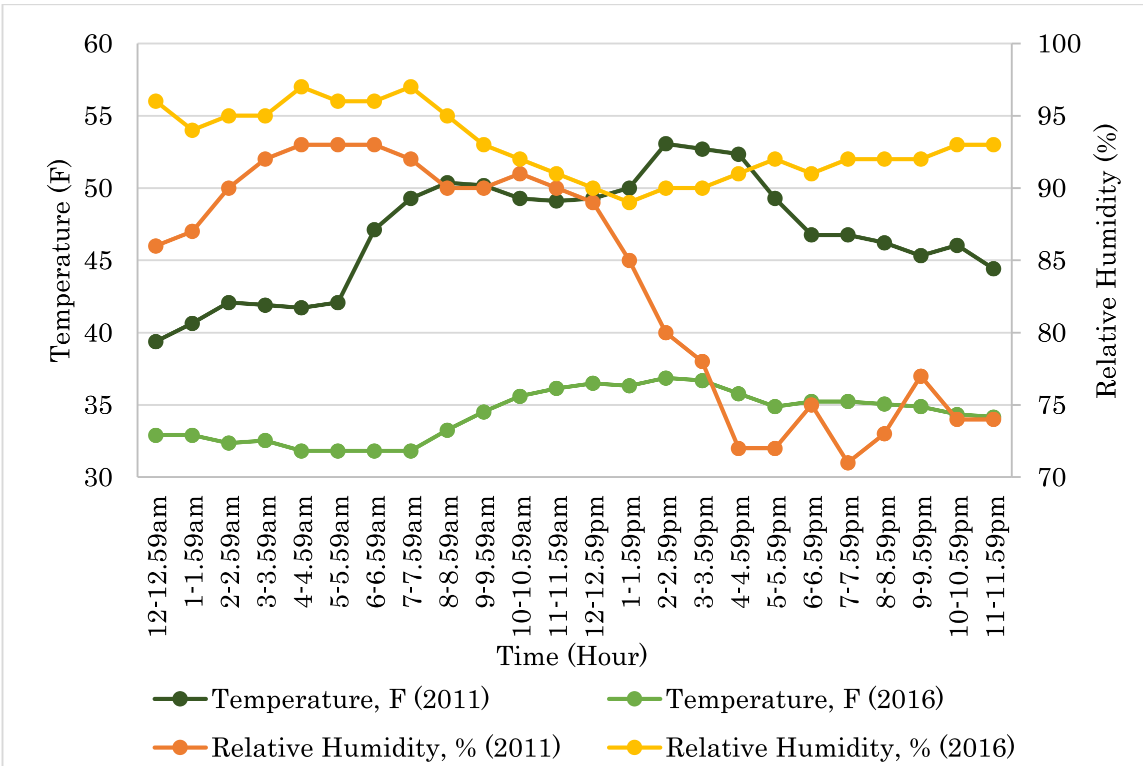


Figure 4-3 Hourly Profile of Environment Temperature and Relative Humidity

Vehicle type VMT distribution, vehicle type distribution and average speed distribution for each road type are obtained from the simulation results of Halifax Regional Transport Network Model. Generally, MOVES deals with five types of roads. All roads of Halifax fall in the category of urban unrestricted, urban restricted and rural unrestricted access road type in MOVES. Although, some passenger cars use diesel fuel, for simplicity this study assumes that all passenger cars use gasoline fuel and all trucks use diesel fuel. MOVES considers multiple sources to estimate the emission of pollutants, for example, running exhaust, start exhaust, break wear, tire wear, evaporative fuel leaks, auxiliary power exhaust and others.

After the preprocessing phase, the next stage executes the emission model through multiple iterations within MOVES. Five emission rates are estimated in the execution phase such as 'Rateperdistance ($R_{perdistance}$)', 'Ratepervehicle ($R_{pervehicle}$)', 'Rateperstart ($R_{perstart}$)', 'Rateperhour ($R_{perhour}$)', and 'Rateperprofile ($R_{perprofile}$)'. The emission rates vary depending on the developed inventories in the pre-processing phase and can be expressed as:

$$R_{perdistance} = f(\theta, r, s, m, f) \quad (15)$$

$$R_{pervehicle} = f(\theta, m, f, d, h) \quad (16)$$

$$R_{perstart} = f(\theta, m, f, d, h) \quad (17)$$

$$R_{perhour} = f(\theta, m, f, d, h) \quad (18)$$

$$R_{perprofile} = f(\theta, m, f, d, h) \quad (19)$$

Where, θ, m, f, d, h, r, and h represent the temperature, model year, fuel type, day type, hour of day, road type and speed bin respectively.

Total activity by fleets e.g., vehicle population, vehicle mile travelled (VMT), and others are estimated in the inventory mode. Then, in the last step i.e. post-processing generates output script that contains the disaggregated emission results for all pollutants. The post-processing of results involves multiplying the rate with appropriate activity to calculate emission resulting from different source types such as total running emission ($E_{running}$), total start emission (E_{start}), total hotelling emission ($E_{hotelling}$), and total evaporative emission ($E_{evaporative}$), where,

$$E_{running} = R_{perdistance} * VMT \qquad (20)$$

$$E_{start} = R_{perstart} * vehicle\ population \qquad (21)$$

$$E_{hotelling} = R_{pervehicle} * number\ of\ source\ type \qquad (22)$$

$$E_{evaporative} = R_{perprofile} * number\ of\ vehicles \qquad (23)$$

The total emission ($E_{aggregate}$) is then referred to the aggregation of all types of emissions and can be expressed as follows:

$$E_{aggregate} = E_{running} + E_{start} + E_{hotelling} + E_{evaporative} \qquad (24)$$

4.4 Results from 2011 model

4.4.1 Comparison of Zonal Emission

Table 4-2 presents a summary of zonal emission of GHG, CO, NOx, PM_{10}, $PM_{2.5}$, and THC for the morning peak, mid-day and evening peak period in Halifax. The zonal average emission of each pollutant for three time periods are also shown in the Table. The results reveal that 50% of total TAZs in Halifax experience an emission below the average emission of all TAZs for all time periods. That implies, significantly low emission occurs in the wide spread peripheral rural TAZs.

Table 4-2 Emission Results of TAZs in the Halifax Transport Network

Pollutant	Time	Minimum (g/km²)	25 Percentile (g/km²)	Median (g/km²)	Average (g/km²)	75 Percentile (g/km²)	Maximum (g/km²)	% Change with respect to Mid-day
GHG	AM Peak	21.34	185.55	345.03	709.19	851.67	4,242.57	17.24%
	Mid-day	18.20	158.27	294.29	604.90	726.43	3,618.66	-
	PM Peak	23.22	201.93	375.47	754.80	926.82	4,616.92	27.59%
CO	AM Peak	0.47	4.10	7.62	15.66	18.81	93.71	3.23%
	Mid-day	0.46	3.97	7.38	15.18	18.22	90.78	-
	PM Peak	0.54	4.74	8.81	17.71	21.75	108.35	19.35%
NOx	AM Peak	0.06	0.48	0.90	1.84	2.21	11.02	10.00%
	Mid-day	0.05	0.44	0.81	1.67	2.01	10.02	-
	PM Peak	0.06	0.54	1.00	2.02	2.48	12.35	23.33%
PM_{10}	AM Peak	0.08	0.73	1.35	2.78	3.33	16.61	- 42.5%
	Mid-day	0.15	1.26	2.35	4.83	5.80	28.88	-
	PM Peak	0.13	1.17	2.17	4.37	5.36	26.72	- 7.50%
$PM_{2.5}$	AM Peak	0.07	0.60	1.12	2.30	2.77	13.78	- 37.5%
	Mid-day	0.11	0.96	1.79	3.68	4.43	22.04	-
	PM Peak	0.10	0.84	1.57	3.15	3.87	19.29	- 12.5%
SO2	AM Peak	0.08	0.72	1.34	2.75	3.30	16.46	3.23%
	Mid-day	0.08	0.70	1.30	2.67	3.20	15.94	-
	PM Peak	0.10	0.83	1.55	3.11	3.82	19.03	16.73%
THC	AM Peak	0.52	4.53	8.42	17.31	20.79	103.55	- 3.13%
	Mid-day	0.54	4.67	8.69	17.87	21.46	106.89	-
	PM Peak	0.62	5.41	10.05	20.21	24.81	123.59	15.63%
VOC	AM Peak	0.47	4.10	7.62	15.66	18.81	93.71	- 3.03%
	Mid-day	0.49	4.23	7.86	16.15	19.40	96.64	-
	PM Peak	0.52	4.48	8.34	16.76	20.58	102.49	6.06%

In the case of all pollutants, except PM_{10}, and $PM_{2.5}$, the rate of emission is higher in the evening peak period. Emission of GHG, CO, NOx, PM_{10}, $PM_{2.5}$, SO_2 and THC and VOC are 754.80gm/km², 17.71 gm/km², 2.02 gm/km², 4.37 gm/km², 3.15 gm/km², 3.11 gm/km², 20.21 gm/km², and 16.76 gm/km² respectively in evening peak hour. For PM_{10} and $PM_{2.5}$, the emissions are higher at mid-day with numerical values as 4.83 and 3.68 gm/km^2 respectively, which indicates the significant contribution of high truck flow at mid-day to the emission of the pollutant PM_{10} and $PM_{2.5}$. Overall, the total emissions are relatively low at mid-day with respect to other periods (morning and evening) of the day. It has been found that compared to the emission of mid-day, the increase in emission of the GHG, CO, NOx, SO_2, THC and VOC in the evening peak period is higher than that of the morning peak period. The results implicate that evening peak hour is critical in terms of emissions when congestion peaks and both the passenger car and truck contribute significantly to the emissions.

4.4.2 Hourly Profiles for Total Emission of Pollutants

Table 4-3 presents hourly profile of emission from passenger car for all pollutants. In the Table, wider bar represents larger values of emission. The colored bars represent a similar pattern of volume in case of passenger car which generates the highest emission during morning and evening peak period. Total emission of GHG, CO, NOx, PM_{10}, $PM_{2.5}$, SO_2, THC, and VOC from passenger car during evening peak hour is 142.09 ton, 0.75 ton, 0.05 ton, 0.0005 ton, 0.0004 ton, 0.0004 ton, 0.02 ton, and 0.01 ton respectively within the HRM. The lowest emission is found from 2:00am to 2:59am and the corresponding values are 2.45 ton, 0.01 ton, 0.0 ton, 0.0 ton, 0.0 ton, 0.0 ton, 0.0 ton, and 0.0 ton respectively. This table also offers the results on daily total emission of these pollutants from passenger car and the values are 5257.24 ton, 1563.51 ton, 8.31 ton, 0.31 ton, 0.0056 ton, 0.0054 ton, 0.0049 ton, 0.18 ton, and 0.17 ton respectively.

Table 4-3 Hourly Profile for Total Emission from Passenger Car

Mode	Time	GHG (ton)	CO (ton)	NOx (ton)	PM_{10} (ton)	$PM_{2.5}$ (ton)	SO_2 (ton)	THC (ton)	VOC (ton)
Passenger Car	12:00-12:59am	11.62	0.06	0.00	0.0001	0.0001	0.0000	0.00	0.00
	1:00-1:59am	3.48	0.02	0.00	0.0000	0.0000	0.0000	0.00	0.00
	2:00-2:59am	2.45	0.01	0.00	0.0000	0.0000	0.0000	0.00	0.00
	3:00-3:59am	10.26	0.05	0.00	0.0000	0.0000	0.0000	0.00	0.00
	4:00-4:59am	22.56	0.12	0.00	0.0001	0.0001	0.0001	0.00	0.00
	5:00-5:59am	33.10	0.17	0.01	0.0001	0.0001	0.0001	0.00	0.00
	6:00-6:59am	86.51	0.45	0.02	0.0003	0.0003	0.0003	0.01	0.01
	7:00-7:59am	115.36	0.62	0.02	0.0004	0.0004	0.0004	0.01	0.01
	8:00-8:59am	137.62	0.72	0.03	0.0005	0.0005	0.0004	0.02	0.01
	9:00-9:59am	101.56	0.53	0.02	0.0003	0.0003	0.0003	0.01	0.01
	10:00-10:59am	84.68	0.45	0.02	0.0003	0.0003	0.0003	0.01	0.01
	11:00-11:59am	68.24	0.37	0.01	0.0002	0.0002	0.0002	0.01	0.01
	12:00-12:59pm	71.14	0.39	0.01	0.0003	0.0002	0.0002	0.01	0.01
	1:00-1:59pm	54.58	0.30	0.01	0.0002	0.0002	0.0002	0.01	0.01
	2:00-2:59pm	82.97	0.45	0.02	0.0003	0.0003	0.0003	0.01	0.01
	3:00-3:59pm	107.06	0.56	0.02	0.0003	0.0003	0.0003	0.01	0.01
	4:00-4:59pm	142.09	0.75	0.03	0.0005	0.0004	0.0004	0.02	0.01
	5:00-5:59pm	114.36	0.61	0.02	0.0004	0.0004	0.0004	0.01	0.01
	6:00-6:59pm	87.04	0.47	0.02	0.0003	0.0003	0.0003	0.01	0.01
	7:00-7:59pm	78.74	0.42	0.02	0.0003	0.0003	0.0002	0.01	0.01
	8:00-8:59pm	55.92	0.30	0.01	0.0002	0.0002	0.0002	0.01	0.01
	9:00-9:59pm	44.73	0.24	0.01	0.0002	0.0002	0.0001	0.01	0.00
	10:00-10:59pm	29.12	0.16	0.01	0.0001	0.0001	0.0001	0.00	0.00
	11:00-11:59pm	18.37	0.10	0.00	0.0001	0.0001	0.0001	0.00	0.00
Daily Total Emission from Passenger Car		**1563.51**	**8.31**	**0.31**	**0.0056**	**0.0054**	**0.0049**	**0.18**	**0.17**

Table 4-4 presents hourly profile of emission from different types of trucks. Emission generated from trucks also poses similar pattern of their hourly volume profile. Maximum emission occurs during mid-day period starting from 11:00am to 12:59pm. Among commercial vehicles, heavy truck is the main contributor to the emission of GHG, NOx, PM_{10}, $PM_{2.5}$, and SO_2. Light truck significantly contributes to the emission of CO, THC, and VOC. Medium truck causes comparatively less emission compared to other trucks. Total daily emission of GHG, CO, NOx, PM_{10}, $PM_{2.5}$, SO_2, THC, and VOC generated from all trucks is 3706.19 ton, 33.84 ton, 6.41 ton, 0.1249 ton, 0.1143 ton, 0.0992 ton, 2.32 ton, and 2.34 ton respectively. Hourly profile of emission from all vehicles for all the pollutants are shown using line diagram in Appendix H (Figure H-1, Figure H-2, and Figure H-3).

Table 4-4 Hourly Profile for Total Emission from Different Truck Types

Truck Types	Time	GHG (ton)	CO (ton)	NOx (ton)	PM_{10} (ton)	$PM_{2.5}$ (ton)	SO_2 (ton)	THC (ton)	VOC (ton)
Light Truck	7:00-7:59am	88.21	2.84	0.19	0.0004	0.0004	0.0022	0.22	0.21
	8:00-8:59am	119.77	3.04	0.24	0.0005	0.0004	0.0030	0.24	0.22
	11:00-11:59am	238.19	3.67	0.42	0.0006	0.0005	0.0061	0.27	0.25
	12:00-12:59pm	252.21	3.48	0.42	0.0006	0.0005	0.0065	0.25	0.24
	4:00-4:59pm	121.56	2.72	0.26	0.0004	0.0003	0.0030	0.21	0.20
	5:00-5:59pm	112.29	2.60	0.26	0.0005	0.0004	0.0028	0.21	0.20
Medium Truck	7:00-7:59am	71.48	0.36	0.03	0.0006	0.0005	0.0005	0.02	0.03
	8:00-8:59am	111.57	1.20	0.04	0.0008	0.0008	0.0008	0.05	0.07
	11:00-11:59am	213.15	0.98	0.10	0.0017	0.0016	0.0015	0.06	0.09
	12:00-12:59pm	191.44	0.79	0.09	0.0016	0.0015	0.0014	0.05	0.07
	4:00-4:59pm	136.09	0.54	0.06	0.0011	0.0011	0.0009	0.03	0.05
	5:00-5:59pm	84.67	0.29	0.04	0.0007	0.0007	0.0006	0.02	0.03
Heavy Truck	7:00-7:59am	216.00	1.40	0.46	0.0126	0.0116	0.0077	0.08	0.08
	8:00-8:59am	304.29	1.89	0.65	0.0178	0.0163	0.0108	0.11	0.11
	11:00-11:59am	475.16	2.65	1.03	0.0279	0.0255	0.0169	0.16	0.17
	12:00-12:59pm	332.20	1.88	0.72	0.0195	0.0179	0.0118	0.12	0.12
	4:00-4:59pm	363.79	2.00	0.80	0.0214	0.0196	0.0129	0.12	0.13
	5:00-5:59pm	274.12	1.52	0.61	0.0161	0.0147	0.0097	0.09	0.09
Daily Total Emission from Trucks		**3706.19**	**33.84**	**6.41**	**0.1249**	**0.1143**	**0.0992**	**2.32**	**2.34**

4.4.3 Daily Link Based Emission of GHG

This study evaluated the daily total link-based emissions of GHG contributed by all modes in the Halifax transport network. Urban core, bridges and the highway links exhibit the highest emission. Highway 101, 102 and 103 connect downtown core with other parts of Halifax. These results indicate that high emission emitters stay in suburban zones which are less emission prone areas. Hourly link-based emission of GHG is enclosed in Appendix I. These maps illustrate the hourly changes in GHG emission within the road network. This study identifies that, most of the GHG emission occurs during evening peak hour starting from 4:00pm to 4:59 pm.

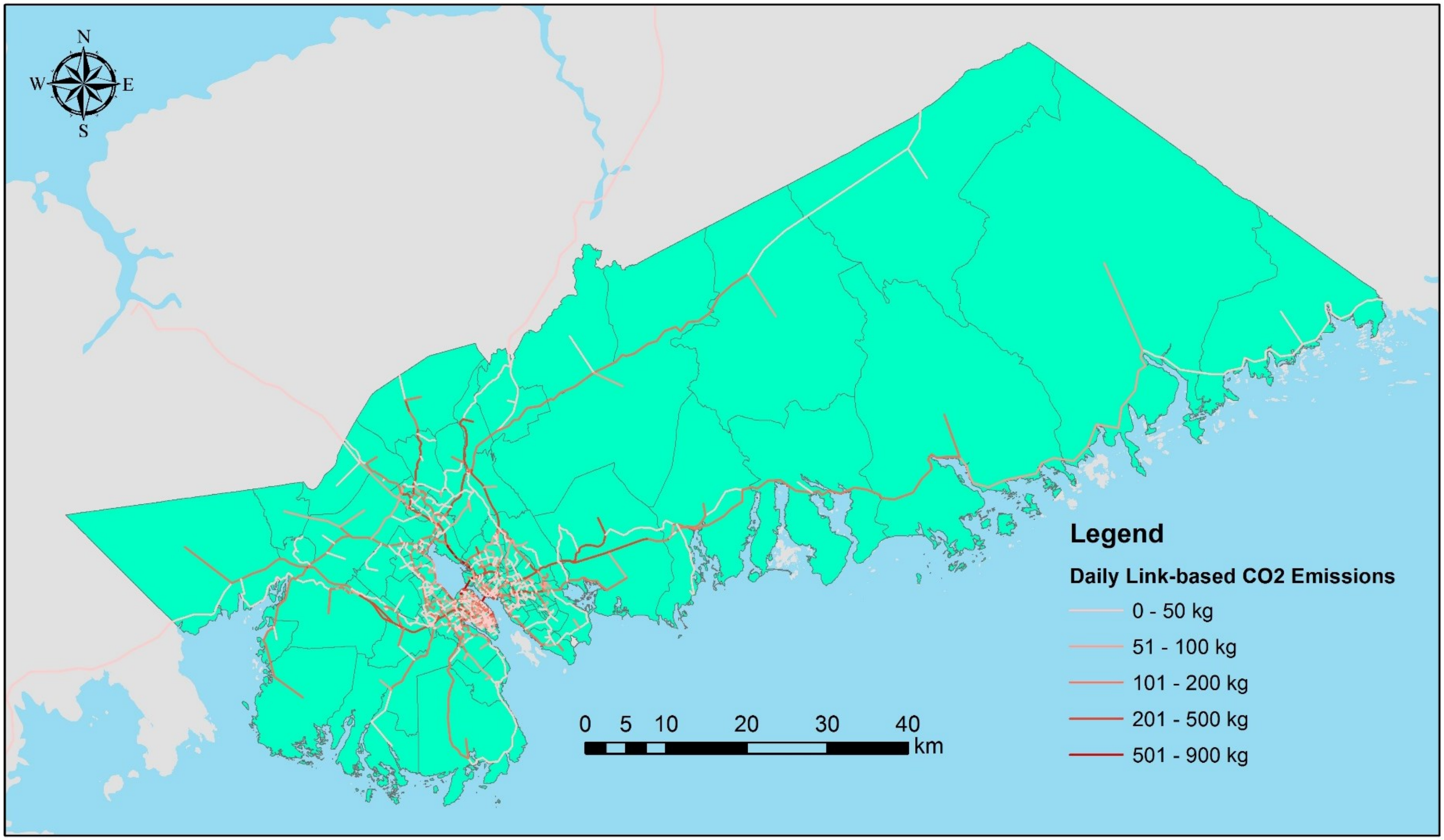


Figure 4-4 Daily Link-based GHG Emission for the Year of 2011 within Halifax Transport Network Model

4.4.4 Spatial Distribution of GHG Emission

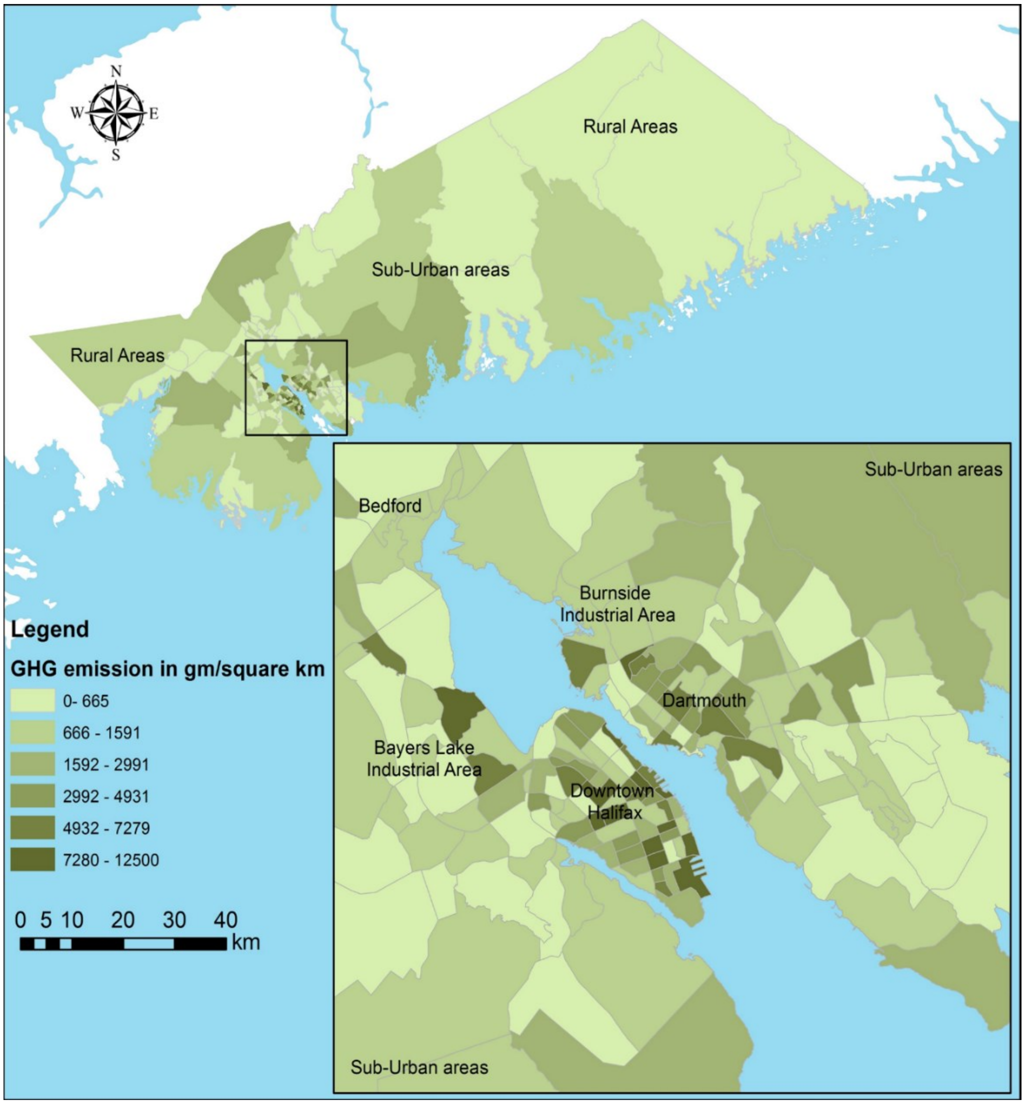


Figure 4-5 Spatial Distribution of GHG Emission within HRM

This study investigates the spatial distribution of CO_2 within HRM, which is a major contributor to the GHG emission (Figure 4-5). It is evident from the illustration that most of the GHG emission is concentrated in the urban core area. The dense urban core of HRM, centered on the Halifax Peninsula and the core area of Dartmouth (inside of the Circumferential Highway) has a population of 316,701 which is 78.56 % of total population *(Statistics Canada, 2012)*. The average concentration of GHG for this area is estimated as 3,677.33

gm/km^2. In contrast, the average concentration for entire HRM is 2,057. gm/km^2 which is almost half of the urban GHG concentration. Moreover, sub urban area such as Bedford, and Burnside has also significant concentration of GHG which is on average 1,126.51 gm/km^2. Other pollutant also exhibits similar patterns.

4.4.5 Temporal Variation of Emission by Vehicle Types

Figure 4-6 shows the temporal variation of emissions contributed by different modes (passenger car, light commercial vehicle, single unit short haul truck and combination of long haul truck) in the Halifax transport network. The percent contribution to the pollutants, particularly CO, NOx, PM_{10}, and $PM_{2.5}$ by each mode in each period is estimated and compared. The concentration of these pollutants in the atmosphere is significantly related to heavy duty diesel vehicles *(Gajendran and Clark, 2003).* Emission from passenger car retained for comparison purpose. For example, in the PM peak period, the combination long haul trucks contribute to the emission of CO_2, CO, NOx, PM_{10}, $PM_{2.5}$, and THC at a rate of 47.06%, 44.16%, 43.09%, 43.88%, 50.14%, and 38.69% respectively, out of the total emission contributions by all modes.

Single unit short haul trucks contribute significantly to the emission ranging from 28.99% to 36.27% of total CO emission, 25.27% to 28.44% of total NOx, 22.06% to 24.53% of total PM_{10}, and 21.53% to 23.85% of total $PM_{2.5}$. Besides, light commercial truck emits comparatively low to the emission of total CO ranging from 16.15% to 20.21%, NOx from 5.37% to 5.54, 4.80% to 5.58 for PM_{10}, and 3.36% to 7.11% for $PM_{2.5}$. In comparison to all types of trucks, passenger cars emit a lower amount of air pollutants ranging from 17.92% to 20.97% of total CO emission, 4.08% to 5.42% of total NOx, 4.43% to 5.49% of total PM_{10}, and 4.13% to 5.76% of total $PM_{2.5}$. The results suggest that diesel-fuelled combination long haul truck produce the greatest amount of CO, NOx, PM_{10}, and $PM_{2.5}$ within these periods.

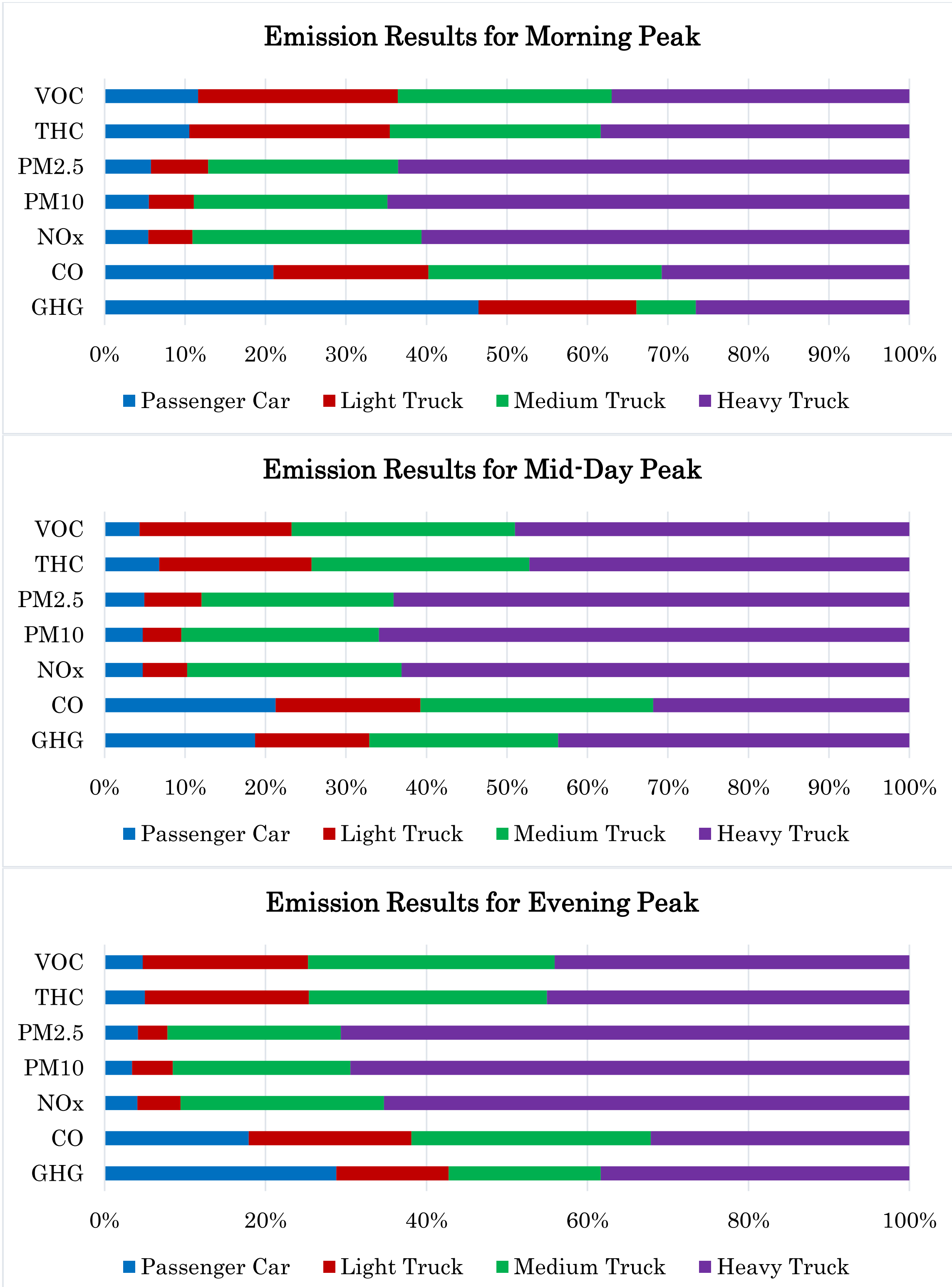


Figure 4-6 Emission Results for (a) Morning Peak (b) Mid-Day Peak and (c) Evening Peak Caused by Different Modes

4.5 Results from 2016 model

4.5.1 Comparison of Zonal Emission

Table 4-5 presents a detailed statistics of emission at TAZ level resulted from all traffic operation in HRM. Emission is higher at urban zones compared to the emission at suburban zones.

Table 4-5 Emission Resulted at Different TAZs in the HRM

Pollutant	Area	Minimum (g/km^2)	25 Percentile (g/km^2)	Average (g/km^2)	Median (g/km^2)	75 Percentile (g/km^2)	Maximum (g/km^2)
GHG	Urban	36.08	543.03	1,562.26	1,210.69	2,473.87	5,106.73
	Suburban	36.42	192.63	383.10	342.55	476.28	1,121.93
	Rural	25.68	148.93	340.64	272.08	490.67	856.17
CO	Urban	2.19	32.92	94.71	73.40	149.97	309.59
	Suburban	2.21	11.68	23.22	20.77	28.87	68.01
	Rural	1.56	9.03	20.65	16.49	29.75	51.90
NOx	Urban	0.16	2.36	6.80	5.27	10.76	22.22
	Suburban	0.16	0.84	1.67	1.49	2.07	4.88
	Rural	0.11	0.65	1.48	1.18	2.14	3.73
PM10	Urban	0.007	0.108	0.309	0.240	0.490	1.011
	Suburban	0.007	0.038	0.076	0.068	0.094	0.222
	Rural	0.005	0.029	0.067	0.054	0.097	0.170
PM2.5	Urban	0.006	0.095	0.274	0.212	0.433	0.895
	Suburban	0.006	0.034	0.067	0.060	0.083	0.197
	Rural	0.004	0.026	0.060	0.048	0.086	0.150
SO2	Urban	0.001	0.010	0.029	0.022	0.045	0.094
	Suburban	0.001	0.004	0.007	0.006	0.009	0.021
	Rural	0.000	0.003	0.006	0.005	0.009	0.016
THC	Urban	0.37	5.61	16.14	12.51	25.56	52.76
	Suburban	0.38	1.99	3.96	3.54	4.92	11.59
	Rural	0.27	1.54	3.52	2.81	5.07	8.85
VOC	Urban	0.37	5.56	15.99	12.39	25.32	52.27
	Suburban	0.37	1.97	3.92	3.51	4.88	11.48
	Rural	0.26	1.52	3.49	2.79	5.02	8.76

Average emission of GHG, CO, NOx, PM_{10}, $PM_{2.5}$, SO_2, THC and VOC in urban areas are 1562.26 gm/km², 94.71 gm/km², 6.8 gm/km², 0.309 gm/km², 0.274 gm/km², 0.029 gm/km², 16.14 gm/km², and 15.99 gm/km². In case of suburban areas, these values are 383.1 gm/km², 23.22 gm/km², 1.67 gm/km², 0.076 gm/km², 0.067 gm/km², 0.007 gm/km², 3.96 gm/km², and 3.92 gm/km² respectively. Rural areas experience less emission compared to urban and suburban areas.

4.5.2 Hourly Profiles for Total Emission of Pollutants

Table 4-6**Error! Not a valid bookmark self-reference.** presents hourly profile of emission from passenger car for all pollutants. Here, wider bar represents larger values of emission.

Table 4-6 Hourly Profile for Total Emission from Passenger Car

Mode	Time	GHG (ton)	CO (ton)	NOx (ton)	PM_{10} (ton)	$PM_{2.5}$ (ton)	SO_2 (ton)	THC (ton)	VOC (ton)
Passenger Car	12:00-12:59am	9.05	0.28	0.02	0.00	0.00	0.00	0.05	0.06
	1:00-1:59am	12.54	0.38	0.02	0.00	0.00	0.00	0.07	0.09
	2:00-2:59am	1.90	0.06	0.00	0.00	0.00	0.00	0.01	0.01
	3:00-3:59am	6.26	0.19	0.01	0.00	0.00	0.00	0.04	0.04
	4:00-4:59am	12.35	0.38	0.02	0.00	0.00	0.00	0.07	0.09
	5:00-5:59am	37.20	1.14	0.07	0.00	0.00	0.00	0.21	0.26
	6:00-6:59am	84.28	2.57	0.16	0.01	0.01	0.00	0.48	0.59
	7:00-7:59am	206.76	6.31	0.38	0.03	0.02	0.00	1.19	1.45
	8:00-8:59am	183.63	5.61	0.34	0.02	0.02	0.00	1.05	1.29
	9:00-9:59am	93.58	2.86	0.17	0.01	0.01	0.00	0.54	0.66
	10:00-10:59am	93.20	2.85	0.17	0.01	0.01	0.00	0.53	0.66
	11:00-11:59am	104.54	3.19	0.19	0.01	0.01	0.00	0.60	0.74
	12:00-12:59pm	118.23	3.61	0.22	0.01	0.01	0.00	0.68	0.83
	1:00-1:59pm	80.91	2.47	0.15	0.01	0.01	0.00	0.46	0.57
	2:00-2:59pm	120.26	3.67	0.22	0.01	0.01	0.00	0.69	0.85
	3:00-3:59pm	111.94	3.42	0.21	0.01	0.01	0.00	0.64	0.79
	4:00-4:59pm	147.73	4.51	0.27	0.02	0.02	0.00	0.85	1.04
	5:00-5:59pm	151.05	4.61	0.28	0.02	0.02	0.00	0.87	1.06
	6:00-6:59pm	115.96	3.54	0.22	0.01	0.01	0.00	0.66	0.82
	7:00-7:59pm	88.43	2.70	0.16	0.01	0.01	0.00	0.51	0.62
	8:00-8:59pm	61.04	1.86	0.11	0.01	0.01	0.00	0.35	0.43
	9:00-9:59pm	50.18	1.53	0.09	0.01	0.01	0.00	0.29	0.35
	10:00-10:59pm	40.18	1.23	0.07	0.00	0.00	0.00	0.23	0.28
	11:00-11:59pm	35.58	1.09	0.07	0.00	0.00	0.00	0.20	0.25
Daily Total Emission from Passenger Car		1966.76	60.06	3.65	0.242	0.214	0.026	11.28	13.84

The colored bars show a similar pattern of volume in case of passenger car which generates highest emission during morning peak period. Total emission of GHG, CO, NOx, PM_{10}, $PM_{2.5}$, SO_2, THC, and VOC from passenger car during morning peak hour is 206.76 ton, 6.31 ton, 0.38 ton, 0.03 ton, 0.02 ton, 0.0 ton, 1.19 ton, and 1.45 ton respectively within the HRM. The lowest emission is found from 2:00am to 2:59am and the corresponding values are 1.9 ton, 0.06 ton, 0.0 ton, 0.0 ton, 0.0 ton, 0.0 ton, 0.01 ton, and 0.01 ton respectively. This table also offers daily total emission of these pollutants from passenger car and the values are 1966.76 ton, 60.06 ton, 3.65 ton, 0.0242 ton, 0.214 ton, 0.026 ton, 11.28 ton, and 13.84 ton respectively.

Table 4-7 Hourly Profile for Total Emission from Different Truck Types

Truck Types	Time	GHG (ton)	CO (ton)	NOx (ton)	PM_{10} (ton)	$PM_{2.5}$ (ton)	SO_2 (ton)	THC (ton)	VOC (ton)
Delivery Truck	7:00-7:59am	22.88	2.05	0.09	0.00	0.00	0.00	0.59	0.59
	8:00-8:59am	63.55	5.69	0.24	0.01	0.01	0.00	1.63	1.65
	9:00-9:59am	109.69	9.82	0.42	0.02	0.01	0.00	2.81	2.84
	10:00-10:59am	129.64	11.61	0.49	0.02	0.01	0.00	3.32	3.36
	11:00-11:59am	134.39	12.03	0.51	0.02	0.02	0.00	3.44	3.48
	12:00-12:59pm	122.52	10.97	0.46	0.02	0.01	0.00	3.14	3.17
	1:00-1:59pm	109.31	9.79	0.41	0.02	0.01	0.00	2.80	2.83
	2:00-2:59pm	95.03	8.51	0.36	0.01	0.01	0.00	2.43	2.46
	3:00-3:59pm	79.61	7.13	0.30	0.01	0.01	0.00	2.04	2.06
	4:00-4:59pm	66.69	5.97	0.25	0.01	0.01	0.00	1.71	1.73
	5:00-5:59pm	55.71	4.99	0.21	0.01	0.01	0.00	1.43	1.44
	6:00-6:59pm	44.23	3.96	0.17	0.01	0.00	0.00	1.13	1.15
	7:00-7:59pm	37.28	3.34	0.14	0.01	0.00	0.00	0.95	0.97
	8:00-8:59pm	30.08	2.69	0.11	0.00	0.00	0.00	0.77	0.78
Long Haul Truck	7:00-7:59am	53.14	3.79	0.35	0.01	0.01	0.00	0.39	0.32
	8:00-8:59am	148.36	10.57	0.96	0.04	0.04	0.00	1.08	0.89
	9:00-9:59am	254.21	18.12	1.65	0.07	0.06	0.01	1.86	1.52
	10:00-10:59am	303.10	21.60	1.97	0.08	0.08	0.01	2.22	1.81
	11:00-11:59am	313.30	22.33	2.04	0.09	0.08	0.01	2.29	1.87
	12:00-12:59pm	286.10	20.39	1.86	0.08	0.07	0.01	2.09	1.71
	1:00-1:59pm	258.89	18.45	1.68	0.07	0.07	0.01	1.89	1.55
	2:00-2:59pm	219.35	15.63	1.43	0.06	0.06	0.00	1.60	1.31
	3:00-3:59pm	185.35	13.21	1.21	0.05	0.05	0.00	1.36	1.11
	4:00-4:59pm	155.59	11.09	1.01	0.04	0.04	0.00	1.14	0.93
	5:00-5:59pm	129.23	9.21	0.84	0.04	0.03	0.00	0.94	0.77
	6:00-6:59pm	103.30	7.36	0.67	0.03	0.03	0.00	0.76	0.62
	7:00-7:59pm	87.15	6.21	0.57	0.02	0.02	0.00	0.64	0.52
	8:00-8:59pm	70.99	5.06	0.46	0.02	0.02	0.00	0.52	0.42
Daily Total Emission from Trucks		**3668.66**	**281.58**	**20.87**	**0.87**	**0.77**	**0.08**	**46.95**	**43.85**

Table 4-7 presents hourly profile of emission from delivery and long haul trucks. Emission generated from these trucks also poses similar pattern of their hourly volume profile. Maximum emission occurs during mid-day period starting from 11:00am to 12:59pm. Compared to delivery truck, long haul truck is the main contributor to the emission of GHG, CO, NOx, PM_{10}, $PM_{2.5}$, and SO_2. Delivery truck significantly contributes to the emission of THC, and VOC. Total daily emission of GHG, CO, NOx, PM_{10}, $PM_{2.5}$, SO_2, THC, and VOC generated from all trucks is 3668.66 ton, 281.58 ton, 20.87 ton, 0.87 ton, 0.77 ton, 0.08 ton, 46.95 ton, and 43.85 ton respectively.

4.5.3 Daily Link Based Emission of Pollutants

This study evaluated the daily total link based GHG emissions contributed by all modes for the year of 2016 (Figure 4-7). Like the previous model year, Bridges are the most polluted places. After that Highway 101, 102 and 103 are affected the most. Mainly these routes join downtown core with other parts of Halifax. This study captures the effect of trip chaining behaviour of delivery trucks that results in more emission within the downtown core area. Hourly link-based emission of GHG is enclosed in Appendix J. These maps clearly capture the hourly change of GHG emission within the road network. This study identifies that, maximum GHG emission occurs during evening peak hour starting from 4:00pm to 4:59 pm.

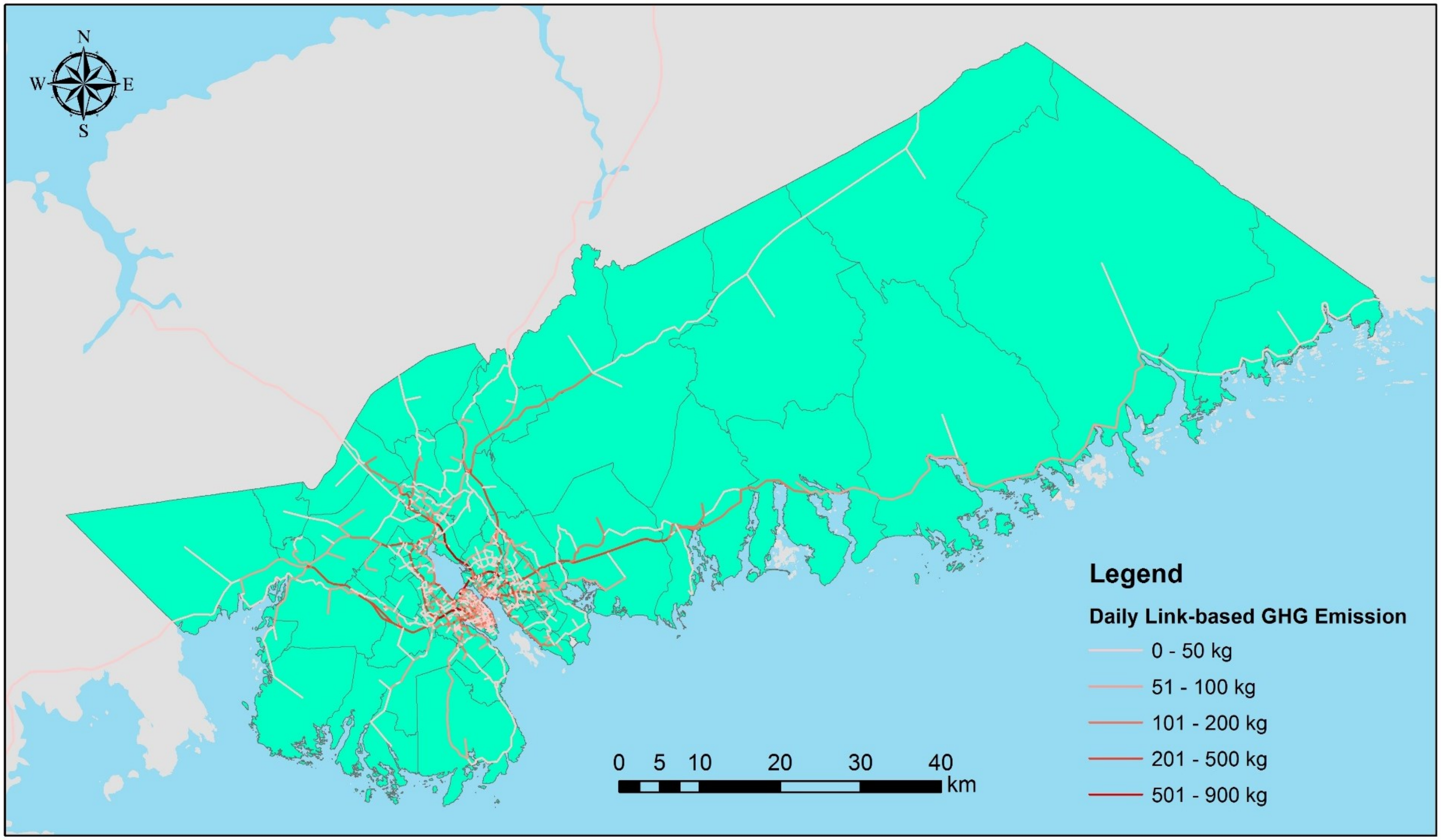


Figure 4-7 Daily Link-based GHG Emission for the year of 2016 within Halifax Transport Network Model

4.5.4 Temporal Variation of Emission by Vehicle Types

Figure 4-8 and Figure 4-9 shows the variation of emissions contributed by passenger car, delivery truck, and long haul truck in different time of the day. Five periods such as early morning (7:00-7:59am), Morning (9:00-9:59am), Midday (12:00-12:59pm), Evening (4:00-4:59pm) and night (8:00-8:59pm) are considered for this study. Percent contribution to all pollutants are estimated and compared for all modes. In early morning period, emission is mainly contributed from passenger car, as the number of trucks in road network remains low at that time. During this time, passenger car contributes to the emission of GHG, CO, NOx, PM_{10}, $PM_{2.5}$, SO_2, THC and VOC at the rate of 44.82%, 33.62%, 20.06%, 44.20%, 43.14%, 46.98%, 29.80%, and 33.86% respectively out of the total emission contributions by all modes. As the day goes on, percentage of emission contributed from passenger car becomes lower as emission contributed from trucks increases. During mid-day period, delivery truck contributes to the emission of GHG, CO, NOx, PM_{10}, $PM_{2.5}$, SO_2, THC and VOC at the rate of 23.97%, 32.03%, 18.94%, 16.35%, 14.59%, 30.30%, 56.71%, and 60.74% respectively and long haul trucks contributes at the rate of 55.96%, 59.53%, 75.82%, 74.53%, 76.64%, 61.56%, 37.83%, and 32.73% respectively.

Passenger cars contribute to the emission ranging from 20.07% to 44.82% of total GHG emission, 8.44% to 33.62% of total CO, 5.24% to 20.06% of total NOx, 9.12% to 44.20% of total PM_{10}, and 8.77% to 43.14% of total $PM_{2.5}$. 8.14% to 46.98% of total SO_2, 5.46% to 29.80% of total THC, 6.54% to 33.86% of total VOC. Delivery trucks contribute to the emission ranging from 16.61% to 23.97% of total GHG emission, 23.30% to 32.03% of total CO, 16.05% to 25.22% of total NOx, 10.08% to 33.21% of total PM_{10}, and 9.13% to 33.30% of total $PM_{2.5}$, 17.55% to 46.45% of total SO_2, 42.20% to 56.71% of total THC, 43.06% to 60.74% of total VOC.

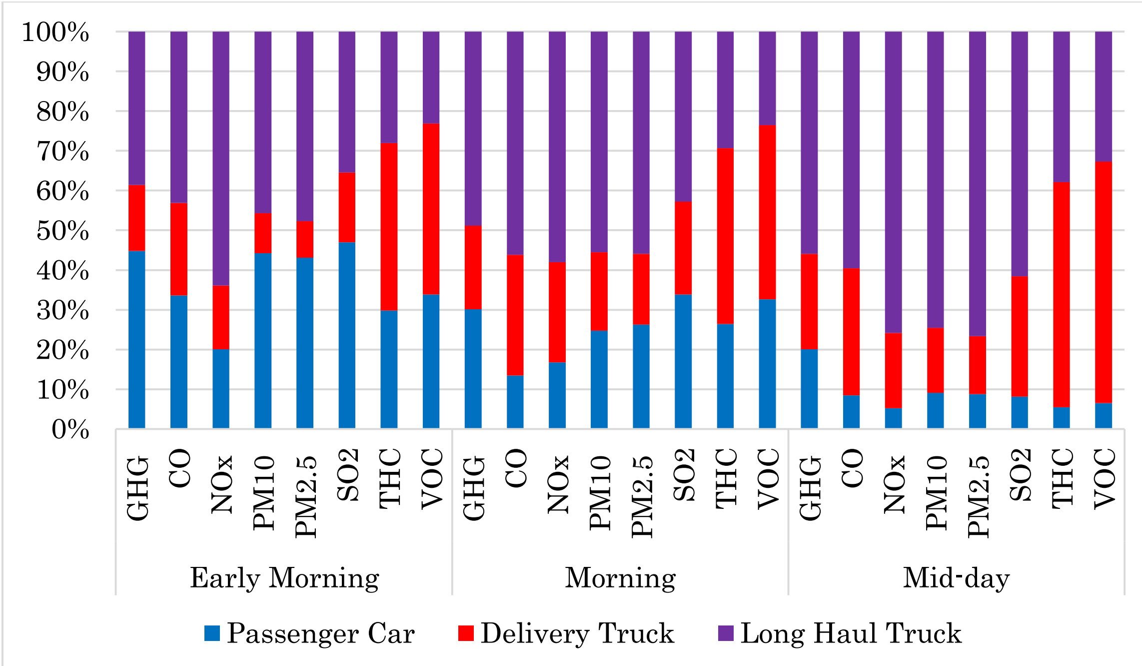


Figure 4-8 Emission Results from Different Modes at Early Morning, Morning and Mid-Day Time Period

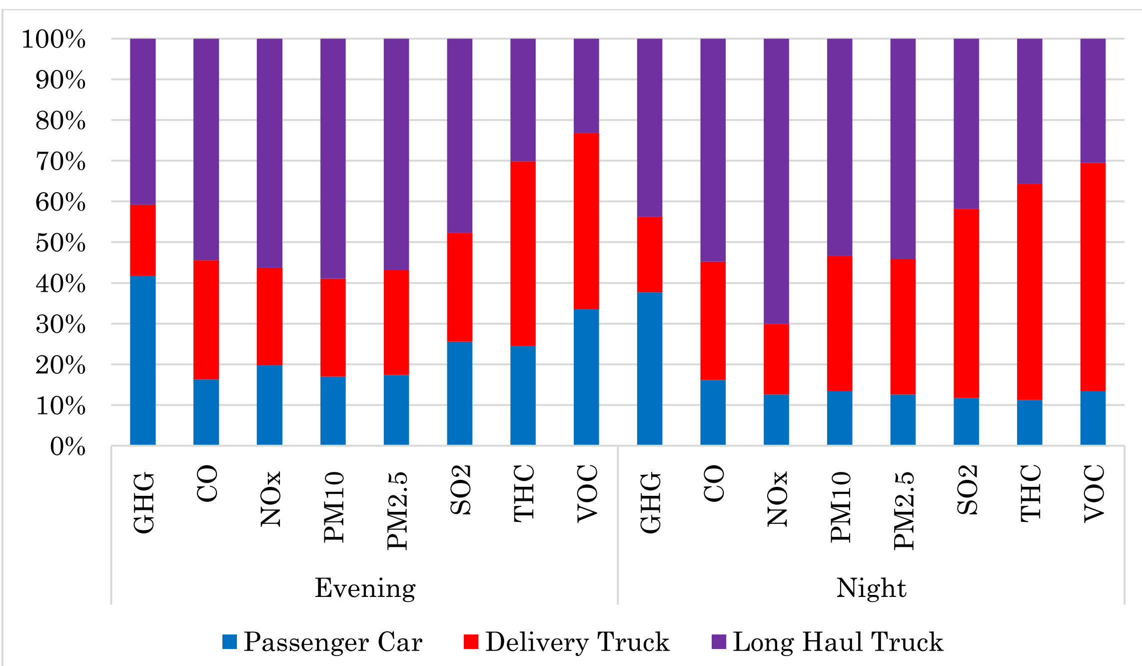


Figure 4-9 Emission Results from Different Modes at Evening and Night Time Period

Long haul trucks contribute significantly to the emission ranging from 38.57% to 55.96% of total GHG emission, 43.08% to 59.53% of total CO, 58.04% to 75.82% of total NOx, 45.72% to 74.53% of total PM_{10}, and 47.73% to 76.64% of total $PM_{2.5}$, 35.47% to 61.56% of total SO_2, 28% to 37.83% of total THC, 23.08% to 32.73% of total VOC. The results suggest that long haul truck produce the greatest amount of GHG, CO, NOx, PM_{10}, and $PM_{2.5}$, and SO_2 within these periods.

4.6 Conclusion

This study quantified the spatial and temporal evaluation of commercial vehicles movement for the port city of Halifax. The results show that commercial vehicles significantly contribute to the network emissions. In the morning, emissions are mainly associated with passenger cars, however as the day goes on emissions increase with the number of trucks on the road. For both models, the maximum emissions are estimated during evening peak period when the maximum number of passenger cars and trucks are present in the road network simultaneously. Emission of GHG, CO, NOx, PM_{10}, $PM_{2.5}$, SO_2 and THC and VOC are 754.80gm/km^2, 17.71 gm/km^2, 2.02 gm/km^2, 4.37 gm/km^2, 3.15 gm/km^2, 3.11 gm/km^2, 20.21 gm/km^2, and 16.76 gm/km^2 respectively in evening peak hour for the model year of 2011. Higher emissions of particulate matters at mid-day clearly indicates the significant contribution of heavy-duty diesel truck flow at that time. Emission results of 2016 model year investigates the emission at different zonal level. This study reveals, emission is higher at urban zones compared to the emission at suburban zones. Average emission of GHG, CO, NOx, PM_{10}, $PM_{2.5}$, SO_2, THC and VOC in urban areas are 1562.26 gm/km^2, 94.71 gm/km^2, 6.8 gm/km^2, 0.309 gm/km^2, 0.274 gm/km^2, 0.029 gm/km^2, 16.14 gm/km^2, and 15.99 gm/km^2. In case of suburban areas, these values are 383.1 gm/km^2, 23.22 gm/km^2, 1.67 gm/km^2, 0.076 gm/km^2, 0.067 gm/km^2, 0.007 gm/km^2, 3.96 gm/km^2, and 3.92 gm/km^2

respectively. Rural areas experience less emission compared to urban and suburban areas. The second model captured the trip changing behaviour of delivery truck which is reflected in higher emission within urban zones.

The multiclass traffic network model can be used by the policy makers to implement different regional-level transport policies for emission reductions in the future. This study provides a baseline emission from a comprehensive multiclass transportation model. These information will be useful for tracking progress to meet the target outlined in the sustainable transportation strategy 2013 adopted by Nova Scotia Department of Energy. The emission results are also relevant to epidemiologic studies of environment pollution and corresponding health issues.

Chapter 5

Conclusion

5.1 Summary of the Research

This research was motivated by the intention of assisting **Canadian Urban Environment and Health Research Consortium (CANUE)** which conducts environmental health research so policy makers and urban regional planners can make evidence-based decisions to help address this challenge. As one of the fastest growing urban areas in Canada, Halifax region is facing challenging issues associated with urban growth such as traffic congestion, economic development, sprawl, social equity, sustainability and public health issues. These challenges urge to better understand how our health is shaped by the structure and function of our cities ('urban form'), so that such knowledge can be used to inform decision-making by multiple levels of government and the private sector. Particularly, to advance understanding of the passenger and good movements and related emissions require harmonizing methodologies to model travel demand for the estimation of traffic congestion, and vehicular emission, and the analysis of the model results, storage, and sharing. Therefore, this thesis presents a comprehensive and sequential framework of travel demand and emission modeling system. This study addresses the deficiencies in the existing travel demand modeling practices by incorporating both the personal travel needs and commercial vehicle movement aspects within a single travel demand modeling platform. Another notable feature of this study is that it conducts a detailed analysis of vehicular emission contributed by passenger cars and commercial vehicles.

The second chapter of this research presents **framework of developing a multiclass travel demand forecasting model** that incorporates both passenger car and different commercial vehicles. This chapter includes an exploration of four stage travel demand modelling system around the world, developing of transport network model including external TAZs, estimation of travel demand for both passenger car and commercial vehicles, and finally assigns all vehicles in a multiclass traffic assignment platform. The transport network model is extensively calibrated and validated to acquire actual traffic condition in the network and the goodness-fit-of the model is confirmed with R^2, GEH and RMSE values. This chapter emphasizes on the evaluation of traffic congestion due to simultaneous operation of personal and commercial vehicle movements in the network. Although commercial vehicles are often neglected in travel demand forecasting modeling, this study reveals that evening peak hour is critical for traffic congestion due to the presence of maximum number of vehicles with a significant proportion of light and heavy trucks in the network.

The third chapter amends the multiclass transport network model developed in the previous chapter by **incorporating delivery truck tours**. The chapter extends an extent of the earlier model by utilizing an enriched data set ('Info Canada Business Establishment' data set) and a tour-based approach accompanied with Monte Carlo simulation technique. The uniqueness of this model is that it captures the trip chaining behavior of the local truck delivery system which is not addressed in the earlier model. This improved model generates truck tour pattern for five establishment types. It has been found that service sector produces the highest delivery truck tour followed by the retail and industry. The results also suggest that delivery truck flow is the maximum during mid-day. On the other hand, passenger car flow peaks at evening peak period. Solely downtown core experiences 45.53% of daily total passenger car flows.

Finally, the fourth chapter of this thesis **integrates the multiclass traffic network model with an emission modelling framework**. This chapter develops an emission modelling framework to estimate emission of major pollutants contributed by different vehicle classes and analyze the results in order to assess the quality of the ambient air. A wide range of results is obtained from the emission model that includes zonal emission, hourly profiles for total emission of major pollutants, daily link-based emission of GHG, spatial distribution of GHG emission, and temporal variation of emission by different modes for the year of 2011 and 2016. The emission model takes different inventories representing local context, traffic characteristics and traffic flow pattern. The multiclass transport network model developed for the year of 2011 and 2016 inform inventory development to capture local traffic context. The overall emission results reveal that urban area is exposed to the highest emission compared to sub urban and rural area. Interestingly, highways and bridges experience significant emission due to peak hour traffic flows between the urban core and other parts of HRM. In terms of time of the day, evening peak period experiences higher GHG emission. In summary, the findings of this research will help policy makers to develop contingency plans of transportation and air quality management.

5.2 Research Contributions

This research significantly contributes to the field of travel demand forecasting and emission modeling. The major contributions of this study are described as follows:

- This study offers a new framework to incorporate commercial vehicle as a part of multiclass transport network modeling system.
- This study offers a newer method for truck delivery modelling that takes a tour-based approach and newer dataset of business establishment of Halifax.

- This study offers new insights regarding traffic flows and emission estimates for the year of 2011 and 2016

5.3 Limitations

This study addressed deficiency in existing urban transport network modeling by developing a tour-based approach for modeling delivery truck movement. However, goods movement modeling by other commercial vehicles took the traditional trip-based approach. Moreover, passenger car modelling component also took four stage trip-based approach. Given the time constraint of this thesis, it was not attempted to develop all components as a more tour-based pieces which remains a limitation and should be attained in future research.

Although we have considered a multiclass modelling framework, which opens up to incorporate any mode within the travel demand forecasting model, this thesis has not considered transit as a part of assignment procedures which could be improved in next modelling effort.

Additionally, this study utilizes the multisource data at different points to develop the travel demand model for the year of 2011 and 2016 based on the data availability during chronological stages of the research. A newer data collection program (such as: NovaTRAC 2018) could be improvised to standardize further model development with one set of data for future years. NovaTRAC is collecting a random sample of 4,000 household for the year of 2018. This dataset could offer a better and effective way to eliminate this limitation.

5.4 Recommendations for Future Research

This study developed a multiclass travel demand forecasting model focusing on the prediction of the combined traffic congestion and resulting emission estimation from both passenger and commercial vehicle movements in the network. Particularly, the modeling approach focused on capturing the trip chaining behaviour of the delivery truck tour. Therefore, this study recommends a tour-based approach for all commercial vehicle modelling components (i.e., light, medium and heavy truck). It will also be useful if we extend an activity based or tour-based approach for the passenger car modelling as well, which will align all methodological approaches towards newer generation of activity-based transport network model. Immediate future work could be incorporating transit into the framework developed in this thesis as the framework includes multiclass traffic assignment procedure. It will be wise to include transit as a part of decision-making tool for comprehensive testing of transportation and transit policies. Lastly, Second-Order Linear Approximation (SOLA) Traffic Assignment is a new feature recently introduced by EMME. This algorithm reaches convergence in fewer iterations than the standard traffic assignment. This assignment method will be useful in future travel demand modeling as the traffic operation will be more complex which will require a higher computation time.

5.5 Policy Implication

The results of multiclass travel demand forecasting model suggest that Halifax transport network involves a sizable number of commercial vehicle activities. This is worsening congestion and causing significant vehicular emission at the downtown core of the city. Policy should include planning for goods movements which is currently inadequate in the integrated mobility plan of Halifax 2018. Trucks access to the Halifax port and other terminal facilities traveling through downtown Halifax, adding heavy vehicles to the streets, and worsening the congestion. The findings of the model can be useful for transportation professionals and planners to plan an alternative corridor that avoids residential area for truck flow and thereby reduces emission exposure of those areas. Alternative rail corridor could also be useful for goods movement in this case.

The results generated by this study will be shared with CANUE towards developing a nation-wide data archive which will be further used for the environmental health research. The results are also useful for CANUE researchers who are utilizing the data obtained from the model for further emission related health studies. For example, several Dalhousie University researchers would use the traffic flow and emission results obtained from the models developed in this study to attain the CANUE objectives. A shapefile containing daily link-based traffic volume was offered to them for their research work in relation to noise and health impacts. These traffic flow datasets will be further used in other emission related health studies of Halifax Regional Municipality area.

Finally, the travel demand forecasting and emission model results will be useful for tracking progress to meet the target outlined in the Sustainable Transportation Strategy 2013 adopted by the Nova Scotia Department of Energy. The aim of the Sustainable Transportation Strategy is to ensure that the transportation systems support healthy communities by helping the community members to drive less distance, move more efficiently, use cleaner energy, and provide access to essential services and employments. The mode choice and VKT results for different zones and links will inform better land use planning within and between the communities, create better access to a diversity of transportation options, and offer better choices for when and how people get to the places they go. Moreover, the urban transport network modeling, particularly, including delivery truck tour component, is a primacy to develop market mechanics and policy for carbon trade policy adopted by the Federal Government of Canada.

Bibliography

Abbey, D. E., Nishino, N., McDonnell, W. F., Burchette, R. J., Knutsen, S. F., Lawrence Beeson, W. and Yang, J. X. (1999) Long-term Inhalable Particles and Other Air Pollutants Related to Mortality in Nonsmokers. *American Journal of Respiratory and Critical Care Medicine*, 159(2), 373–382.

Abou-Senna, H., and Radwan, E. (2014a) Microscopic Assessment of Vehicular Emissions for General Use Lanes and Managed Lanes: Case Study in Orlando, Florida. *Proceedings of the 93rd Annual Meeting of Transportation Research Board*, Washington, D.C., January 12-16 (No.14-5543)

Abou-Senna, H., and Radwan, E. (2014b) Developing a Microscopic Transportation Emissions Model to Estimate Carbon Dioxide Emissions on Limited-access Highways. *Proceedings of the 93rd Annual Meeting of Transportation Research Board*, Washington, D.C., January 12-16 (No.14-5626)

Ambrosini, C., and Routhier, J. L. (2004). Objectives, methods and results of surveys carried out in the field of urban freight transport: an international comparison. *Transport Reviews*, 24(1), 57-77.

Andersen, Z. J., Hvidberg, M., Jensen, S. S., Ketzel, M., Loft, S., Sørensen, M., Tjønneland, A., Overvad, K., and Raaschou-Nielsen, O. (2011) Chronic Obstructive Pulmonary Disease and Long-Term Exposure to Traffic-Related Air Pollution: A Cohort Study. *American Journal of Respiratory and Critical Care Medicine*, 183(4), 455–461.

Area, H. (2010). *Estimating Urban Commercial Vehicle Movements in the Greater Toronto*. McMaster Institute of Transportation and Logistics (MITL), McMaster University at Ontario

Bassok, A., McCormack, E.D., Outwater, M. L., and Ta, C. (2011) Use of Truck GPS Data for Freight Forecasting: Focusing on the Step of Trip Generation. *Proceedings of the 90th Annual Meeting of Transportation Research Board,* Washington, D.C., January 23-27.

Bastida, C., and Holguín-Veras, J. (2009) Freight Generation Models: Comparative Analysis of Regression Models and Multiple Classification Analysis. *Transportation Research Record: Journal of the Transportation Research Board,* No. 2097 (1), 51-61.

Beagan, D., Fischer, M., and Kuppam, A (2007). Quick Response Freight Manual II. FHWA-HOP-08-010. https://ops.fhwa.dot.gov/freight/publications/qrfm2/qrfm.pdf. Accessed July 20, 2017.

Beelen, R., Hoek, G., van Den Brandt, P. A., Goldbohm, R. A., Fischer, P., Schouten, L. J., Jerrett, M., Hughes, E., Armstrong, B., and Brunekreef, B. (2008) Long-Term Effects of Traffic-Related Air Pollution on Mortality in a Dutch Cohort (NLCS-AIR study). *Environment Health Perspectives*, 116(2), 196–202.

Behan, K., Maoh, H. and Kanaroglou, P. (2008) Smart Growth Strategies, Transportation and Urban Sprawl: Simulated Features for Hamilton, Ontario. *Canadian Geographer*, 52(3), 291-308.

Bela, P. L. and Habib, M. A. (2018a) Development of a Freight Traffic Model for Halifax, Canada at 53rd Conference of Canadian Transportation Research Forum (CTRF), Toronto, Canada, 82-89

Bela, P. L., and Habib, M. A. (2018b) Urban Freight Network and Emission Modeling for Port City Halifax, Canada: A Spatial and Temporal Evaluation of Commercial Vehicles Movement. *Proceedings of the 97th Annual Meeting of Transportation Research Board*, Washington, D. C., January 7-11, (No. 18-06689)

Bela, P. L., and Habib, M. A. (2019) Commercial Vehicle Movement Network Modeling for Halifax, Canada: A Tour-Based Model for Local Truck Delivery. *Proceedings of the 98th Annual Meeting of Transportation Research Board*, Washington, D. C., January 13-17, (No. 19-01657)

Boerkamps, J. H. K., Van Binsbergen, A. J., and Bovy, P. H. L. (2000) Modeling Behavioural Aspects of Urban Freight Movement in Supply Chains. *Transportation Research Record: Journal of the Transportation Research Board*, 1725, 17-25.

Brodrick, C.J, Emilio, A. L., Andrew, F. B., Farshchi, M., Li, L. and Deaton, M. (2004) Effect of Vehicle Operation, Weight, and Accessory Use on Emissions from a Modern Heavy-Duty Diesel Truck. *Transportation Research Record: Journal of the Transportation Research Board*, 1880, 119-125

Bryan, J., Weisbrod, G., Martland, C. D. (2008) Rail Freight as a Means of Reducing Roadway Congestion: Feasibility Considerations for Transportation Planning. *Transportation Research Record: Journal of the Transportation Research Board*, 75-83.

Burgess, P. V. (2010). *HRM Travel Demand Model Traffic Analysis Zone Development*

Canada's Big 4 Container Ports Put Focus on Infrastructure (2013). https://www.joc.com/port-news/international-ports/port-metro-vancouver/canada%E2%80%99s-big-4-container-ports-put-focus-infrastructure_20130902.html. Accessed February 28, 2018

Cavalcante, R., and Roorda, M. J. (2010) A Disaggregate Urban Shipment Size/Vehicle-Type Choice Model. *Proceedings of the 89th Annual Meeting of Transportation Research Board,* Washington D. C., January 10-14 (No. 10-3878)

Chitturi, M. V., Shaw, J. W., Campbell IV, J. R., and Noyce, D. A. (2014) Validation of Origin–Destination Data from Bluetooth Reidentification and Aerial Observation. *Transportation Research Record: Journal of the Transportation Research Board*, 2430(1), 116-123

Choi, H. W., and Frey, H. C. (2010) Estimating Diesel Vehicle Emission Factors at Constant and High Speeds for Short Road Segments. *Transportation Research Record: Journal of the Transportation Research Board*, 2158(1), 19-27.

Chow, J. Y. J., Yang, C. H. and Regan, A. C. (2010) State-of-the Art of Freight Forecast Modeling: Lessons Learned and the Road Ahead. *Transportation*, 37 (6), 1011–1030.

Clark, N. N., Kern, J. M., Atkinson, C. M. and Nine, R. D. (2002) Factors Affecting Heavy-Duty Diesel Vehicle Emissions. *Journal of the Air and Waste Management Association*, 52(1), 84-94.

COMEAP (2010) *The Mortality Effects of Long-Term Exposure to Particulate Air Pollution in the United Kingdom*. Technical report, The Committee on the Medical Effects of Air Pollutants

Comi, A., Site, P. D., Filippi, F., and Nuzzolo, A. (2012) Urban Freight Transport Demand Modelling: A State of the Art. *European Transport*, 1–17.

Donnelly, R., Mayburg, A. H., Shen, H., and Leachman, R. (2008) Defining Future Needs. Proceedings from Freight Demand Modeling: Tools For Public-Sector Decision Making. *Proceedings of the 87th Annual Meeting Transportation Research Board,* Washington, D. C., January 13-17

Egbue, O. and Long, S. (2012) Barriers to Widespread Adoption of Electric Vehicles: An Analysis of Consumer Attitudes and Perceptions. *Energy Policy*, 48, 717-729.

Environment and Climate Change Canada (2018) Canadian Environmental Sustainability Indicators: Greenhouse gas emissions. https://www.canada.ca/content/dam/eccc/documents/pdf/cesindicators/greenhouse-gas-emissions/greenhouse-gas-emissions-en.pdf Accessed in July 15, 2018

Environment Canada (2014). Canada's Emission Trends. Cat. No.: En81-18/2014E-PDF, ISSN: 2291-9392. https://ec.gc.ca/ges-ghg/E0533893-A985-4640-B3A2-008D8083D17D/ETR_E%202014.pdf. Accessed July 18, 2016.

Environment Canada (2016) Hourly Data Report for March 1, 2016. Halifax Dockyard, Nova Scotia. http://climate.weather.gc.ca/climate_data/hourly_data_e.html?hlyRange=2004-09-24%7C2017-07-30&dlyRange=%7C&mlyRange=%7C&StationID=43405&Prov=NS&urlExtension=_e.html&searchType=stnName&optLimit=specDate&StartYear=1840&EndYear=2017&selRowPerPage=25&Line=0&searchMethod=contains&txtStationName=Halifax&timeframe=1&Year=2016&Month=3&Day=1# Accessed in February 8, 2017.

Farzaneh, M., and Zietsman, J. (2012) Characterization of Potential Impact of Speed Limit Enforcement on Emissions Reduction. *Proceedings of the 91st Annual Meeting of the Transportation Research Board*, Washington, D.C., January 22-26 (No. 12-2594)

Federal Highway Administration of U.S. Department of Transportation (2013). Annual Vehicle Distance Traveled in Miles and Related Data - 2013 (1) by Highway Category and Vehicle Type. https://www.fhwa.dot.gov/policyinformation/statistics/2013/vm1.cfm#foot5 Accessed August 15, 2017

Figliozzi, M. A., Kingdon, L., and Wilkitzki, A. (2007) *Analysis of Freight Tours in A Congested Urban Area Using Disaggregated Data: Characteristics and Data Collection Challenges.* Technical Report, Portland State University at Portland

Fischer, M., Outwater, M., Cheng, L., Ahanotu, D., and Calix, R. (2005) An Innovative Framework For Modeling Freight Transportation in Los Angeles County. *Transportation Research Record: Journal of the Transportation Research Board, 1906*, 105-112.

Frey, H. C., N. M. Rouphail, and H. Zhai. (2008) Link-Based Emission Factors for Heavy-Duty Diesel Trucks Based on Real-World Data. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 2058(1), 23-32.

Friesz, T. L., Mookherjee, R., Holguín-Veras, J., Rigdon, M. A. (2008) Dynamic Pricing in An Urban Freight Environment. *Transportation Research Part B: Methodological*, 42, 305–324.

Gajendran, P., and Clark, N. N. (2003) Effect of Truck Operating Weight on Heavy-Duty Diesel Emissions. *Environmental Science and Technology*, 37(18), 4309 -4317.

Gingerich, K., Maoh, H., and Anderson, W. (2016) Characterization of International Origin–Destination Truck Movements across Two Major US–Canadian Border Crossings. *Transportation Research Record: Journal of the Transportation Research Board*, 2547, 1-10.

Gong, Q., and Guo, J. Y. (2011) A Firm-Based Freight Demand Modeling Framework: Capturing Intra-Firm Interaction And Joint Logistic Decision-Making. *Proceedings of the 90th Annual Meeting of Transportation Research Board, Washington, D. C.,* January 23-27

Greaves, S., and Figliozzi, M. A. (2008) Commercial Vehicle Tour Data Collection using Passive GPS Technology: Issues and Potential Applications. *Transportation Research Record: Journal of the Transportation Research Board*, 2049

Grenzeback, L. R., Reilly, W. R., Roberts, P. O., and Stowers, J. R. (1989). Urban freeway gridlock study: decreasing the effects of large trucks on peak-period urban freeway congestion. *Transportation Research Record: Journal of the Transportation Research Board*, 1256, 16-26.

Halifax Port Authority. Facilities. http://www.portofhalifax.ca/facilities. Accessed July 27, 2017.

Hankey, S. and Marshall, J. D. (2010) Impacts of Urban form on Future US Passenger-Vehicle Greenhouse Gas Emissions. *Energy Policy*, 38(9), 4880-4887.

Hatzopoulou, M., Santos, B. F. L. and Miller, E. J. (2008) Developing Regional 24-Hour Profiles for Link- Based, Speed-Dependent Vehicle Emissions and Zone-Based Soaks. *Proceedings of the 87th Annual Meeting of the Transportation Research Board*, Washington, D.C., January 13-17 (No. 08-1157)

Health Effects Institute (2010) *Traffic-Related Air Pollution: A Critical Review of the Literature on Emissions, Exposure, and Health Effects*. Special Report 17, HEI Panel on the Health Effects of Traffic-related Air Pollution, Boston, Massachusetts

Hensher, D. A., and Figliozzi, M. (2007) Behavioural Insights into The Modelling Of Freight Transportation And Distribution Systems. *Transportation Research Part B: Methodological*, *41*, 921-923.

Hensher, D. A., and Puckett, S. M. (2005) Refocusing the Modelling Of Freight Distribution: Development of an Economic-Based Framework to Evaluate Supply Chain Behaviour in Response to Congestion Charging. *Transportation*. 32, 573-602.

Holguín-Veras, J, Thorson, E, Ozbay, K. (2004) Preliminary Results of Experimental Economics Application to Urban Goods Modeling Research. *Transportation Research Record: Journal of the Transportation Research Board,* 1873. 2, 9-16.

Holguin-Veras, J. and Patil, G. (2005) Observed Trip Chain Behavior of Commercial Vehicles. *Transportation Research Record: Journal of the Transportation Research Board*, 1906, 74-80

Hunt, J. D., and Stefan, K. J. (2007) Tour-based microsimulation of urban commercial movements. *Transportation Research Part B: Methodological*, 41(9), 981-1013.

Hunt, J. D., Donnelly, R., Abraham, J. E., Batten, C., Freedman, J., Hicks, J., Costinett, P. J. and Upton, W. J. (2001) Design of a Statewide Land Use Transport Interaction Model for Oregon at the 9th World Conference on Transport Research, Seoul, Korea

Hutchinson, B. G. (1974). *Principles of Urban Transport Systems Planning*

IBI Group (2009a) *TPM for Multi-Modal Transportation Forecasting Tools for the Greater Golden Horseshoe Commercial Vehicle Model*. Background Report 7, Ministry of Transportation, Ontario.

IBI Group (2009b) *TPM for Multi-Modal Transportation Forecasting Tools for the GGH: Model Development and Validation Report,* Ministry of Transportation, Ontario.

Irin, S. and Habib, M. A. (2015) Estimation of Link-Based Emission for a Truck Route in the Downtown Halifax, Canada. *Proceedings of the 84th Annual Meeting of the Transportation Research Board,* Washington, D.C., January 9-13 (No. 15-5946)

Jansuwan, S., Christensen, K. M., and Chen, A. (2013) Assessing the Transportation Needs of Low-Mobility Individuals: Case Study of A Small Urban Community in Utah. *Journal of Urban Planning and Development*, 139(2), 104-114.

Kanafani, A. (1983). *Transportation Demand Analysis*

Kawamura, K., Shin, H., McNeil, S., and Ogard, L. (2005) *Business and Site Specific Trip Generation Methodology for Truck Trips*. Project 05-03, Midwest Regional University Transportation Center, University of Wisconsin-Madison. http://www.minds.wisconsin.edu/handle/1793/6958. Accessed April 24, 2017.

Kim, J. J., Smorodinsky, S., Lipsett, M., Singer, B. C., Hodgson, A. T., and Ostro, B. (2004) Traffic-Related Air Pollution Near Busy Roads: The East Bay Children's Respiratory Health Study. *American Journal of Respiratory and Critical Care Medicine*, 170(5), 520–526

Koupal, J., Michaels, H., Cumberworth, M., Bailey, C., and Brzezinski, D. (2002) EPA's Plan for MOVES: A Comprehensive Mobile Source Emissions Model at the 12th CRC On-Road Vehicle Emissions Workshop San Diego, California, April

Künzli, N., Kaiser, R., Medina, S., Studnicka, M., Chanel, O., Filliger, P., Herry, M., Horak, F., Puybonnieux-Texier, V. and Quénel, P. (2000) Public-Health Impact of Outdoor and Traffic-Related Air Pollution: A European Assessment. *The Lancet*, 356(9232), 795–801.

Laden, F., Schwartz, J., Speizer, F. E., and Dockery, D. W. (2006) Reduction in Fine Particulate Air Pollution and Mortality: Extended Follow-Up of the Harvard Six Cities Study. *American Journal of Respiratory and Critical Care Medicine*, 173(6), 667–672.

Manual, H. C. (2000) *Highway Capacity Manual.*

Maoh, H. and Tang, Z. (2012) Determinants of Normal And Extreme Commute Distance In A Sprawled Midsize Canadian City: Evidence from Windsor, Canada. *Journal of Transport Geography*, 25, 50-57.

MariNova Consulting Ltd (2006). *Halifax Inland Terminal and Trucking Options Study.*

Martin, W. A., and McGuckin, N. A. (1998) *Travel estimation techniques for urban planning* (Vol. 365). Washington, DC: National Academy Press.

Mayer, M. D., and Miller, E. J. (2001). *Urban transportation planning*.

McConnell, R., Islam, T., Shankardass, K., Jerrett, M., Lurmann, F., Gilliland, F., Gauderman, J., Avol, E., Künzli, N., and Yao, L. (2010) Childhood Incident Asthma and Traffic-Related Air Pollution at Home and School. *Environmental Health Perspectives*, 1021–1026.

Meyer Mohaddes Associates Inc (1998). *Heavy Duty Truck model and VMT estimation.* Southern California Association of Governments

Natural Resources Canada (2018) Energy Efficiency Trends Analysis Tables - Transportation Sector - Energy Use Analysis. http://publications.gc.ca/site/archivee-archived.html?url=http://publications.gc.ca/collections/collection_2018/rncan-nrcan/M141-10-2018-eng.pdf Accessed in September 14, 2018

Noriega, Y., and Florian, M. (2007) *Multi-class Demand Matrix Adjustment.* CIRRELT.

Nuzzolo, A., and Comi, A. (2014) Urban Freight Demand Forecasting: A Mixed Quantity/Delivery/Vehicle-Based Model. *Transportation Research Part E: Logistics and Transportation Review*, 65, 84-98.

Oketch, T., and Carrick, M. (2005). Calibration and Validation of a Micro-Simulation Model in Network Analysis. *Proceedings of the 84th Annual Meeting of Transportation Research Board,* Washington, DC, January 9-13

Ortuzar, J. D. and Willumsen, L. G. (2011) *Modelling Transport*, 2011, Fourth edition. New York: John Wiley and Sons. ISBN 978-0-470-76039-0

Outwater, M., Islam, N., and Spear, B. (2005) The Magnitude and Distribution of Commercial Vehicles in Urban Transportation. *CD Proceedings of the 84th Annual Meeting of the Transportation Research Board*, Washington D. C., January 9-13

Parsons Brinckerhoff Quade and Douglas, Inc., University of Washington, EcoNorthwest, and KJS Associates, Inc. (1999) *Proposed Design of a Second-Generation Land Use–Transport Model for Oregon*. Oregon Department of Transportation, USA

Parsons Brinckerhoff Quade and Douglas, Inc., University of Washington, EcoNorthwest, and KJS Associates, Inc. (2000) *Revised Design of a Second-Generation Land Use Transport Model for Oregon*. Oregon Department of Transportation, USA

Pendyala, R. M., Shankar, V. N., and McCullough, R. G. (2000) Freight Travel Demand Modeling: Synthesis of Approaches and Development of A Framework. *Transportation Research Record: Journal of the Transportation Research Board,* 1725, 9-16.

Potoglou, D. and Kanaroglou, P. S. (2008) Disaggregate Demand Analyses for Conventional and Alternative Fueled Automobiles; A Review. *International Journal of Sustainable Transportation*, 2(4), 234-259

Rahman, M., and Habib, M. A. (2015) Evaluating Alternative Transit Options in Halifax Using Travel Demand Forecasting Model Informed by a Stated Preference Survey at the 50th Annual Conference of Canadian Transportation Research Forum*,* Montreal, Quebec, May 24-26

Rahman, M., and Habib, M. A. (2015). Evaluating Alternative Transit Options in Halifax Using Travel Demand Forecasting Model Informed by a Stated Preference Survey at the 50^{th} Annual Conference of the Canadian Transportation Research Forum, Montreal, Quebec, May 24

Regan, A. C. and Garrido, R. A. (2001) Modelling Freight Demand and Shipper Behaviour: State of the Art, Future Directions. *Travel Behaviour Research. Elsevier Science.*

Riad, A. M. (2018). *Developing a High-Fidelity GIS-based Travel Demand Model Framework for Improved Network-wide Traffic Estimation* (Doctoral dissertation).

Roorda, M. J., Kwan, H., McCabe, S. (2008) Comparison of GPS and Driver-reported Urban Commercial Vehicle Tours And Stops. *CD Proceedings of the 87^{th} Annual Meeting of the Transportation Research Board*, Washington DC, January 13–17

Ruiter, E. R. (1992) Development of an urban truck travel model for the Phoenix Metropolitan Area. FHWA-A292-314. https://apps.azdot.gov/ADOTLibrary/publications/project_reports/pdf/AZ314.pdf Accessed July 20, 2017.

Russo F and Comi, A. (2002) A General Multi-Step Model for Urban Freight Movements. *Population*, 700 (800,000), 0–900.

Russo, F., Comi, A. (2010) A Modelling System to Simulate Goods Movements at an Urban Scale. *Transportation*, 37(6), 987–1009.

Samimi, A., Mohammadian, A. K., and Kawamura, K. (2010) A Behavioral Freight Movement Microsimulation Model: Method And Data. *Transportation Letters: The International Journal of Transportation Research, 2*, 53-62.

Sánchez-Díaz, I. (2017) Modeling Urban Freight Generation: A Study of Commercial Establishments' Freight Needs. *Transportation Research Part A: Policy and Practice*, 102, 3-17.

Sharman, B. W. (2014) *Behavioural Modelling of Urban Freight Transportation: Activity and Inter-Arrival Duration Models Estimated Using GPS Data*. Doctoral Thesis, University of Toronto.

Sharman, B., and Roorda, M.J. (2011) Analysis of Freight GPS Data: A Clustering Approach for Identifying Trip Destinations. *Proceedings of the 90th Annual Meeting of Transportation Research Board,* Washington, D.C., January 23-27 (No. 2246)

Sider, T., Alam, A., Farrell, W., Hatzopolou, M., Eluru, N. (2013) Evaluating Vehicular Emissions with an Integrated Mesoscopic and Microscopic Traffic Simulation. *Canadian Journal of Civil Engineering,* 41(10), 856-868.

Sider, T., Alam, A., Zukari, M., Dugum, H., Goldstein, N., Eluru, N. and Hatzopoulou, M. (2013) Land–use and Socio-economics as Determinants of Traffic Emissions and Individual Exposure to Air Pollution. *Journal of Transport Geography,* 33, 230-239

Sivanandan, R., Anusha, S. P. and Senthil Raj, S. K. (2008) Evaluation of Vehicular Emissions under Lane- restricted Heterogeneous Traffic Flow. *Proceedings of the 87th Annual Meeting of Transportation Research Board,* Washington, D. C., January 13-17 (No. 08-2175)

Small, K. A., Winston, C. and Evans, C. A. (2012). *Road Work: A New Highway Pricing and Investment Policy*. Washington D. C.: The Brookings Institution Press

Statistics Canada (2012) Halifax, Nova Scotia (Code 1209034) and Canada (Code 01) (table). Census Profile, 2011 Census. Statistics Canada Catalogue no. 98-316-XWE. Released October 24, 2012. http://www12.statcan.gc.ca/census-recensement/2011/dp-pd/prof/index.cfm?Lang=E. Accessed in February 8, 2017.

Stefan, K. J., Mcmillan, J. D. P. and Hunt, J. D. (2005) Urban Commercial Vehicle Movement Model for Calgary, Alberta, Canada. *Transportation Research Record: Journal of the Transportation Research Board,* 1921, 1-10.

Thompson-Graves, S., DuRoss, M., Ratledge, E. and Racca, D. (2006) Developing A Statewide Travel Demand Model from A Person-Based Time Series Household Survey. *Transportation Research Record: Journal of the Transportation Research Board*, 1981, 68-75.

Tozzi, M., Corazza, M. V., and Musso, A. (2013). Recurring patterns of commercial vehicles movements in urban areas: the Parma case study. *Procedia-Social and Behavioral Sciences*, 87, 306-320.

US Environmental Protection Agency (2003). *Greenhouse Gas Emissions from the U.S. Transportation Sector: 1990-2003.* http://epa.gov/otaq/climate/420r06003.pdf. Accessed July 23, 2017

US Environmental Protection Agency (2005). *National Emissions Inventory Air Pollutant Emissions Trends Data.* http://www.epa.gov/ttn/chief/trends/. Accessed in June 29, 2017.

US Environmental Protection Agency (2009) *Motor Vehicle Emission Simulator. Moves 2010 User Guide.* EPA report, EPA-420-B-09-041, Office of Transportation and Air Quality 414

US Environmental Protection Agency (2011) Getting to Smart Growth: 100 Policies for Implementation. Smart Growth Network. http://www.smartgrowth.org/pdf/gettosg.pdf. Accessed May 20, 2018.

US Environmental Protection Agency (2015a) Emission Adjustments for Temperature, Humidity, Air Conditioning, and Inspection and Maintenance for On-road Vehicles in MOVES2014. https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100NOEM.pdf Accessed in April 29, 2017

US Environmental Protection Agency (2015b) MOVES2014a User Guide. https://scholar.google.ca/scholar?hl=en&as_sdt=0%2C5&q=EPA%2C+U.+%282015%29.+MOVES2014a+User+Guide.+EPA-420-B-15095&btnG= Accessed in February 13, 2017

Vallamsundar, S., and Lin, J. J. (2012) MOVES and AERMOD Used for PM 2.5 Conformity Hot Spot Air Quality Modeling. *Transportation Research Record: Journal of the Transportation Research Board,* 2270(1), 39-48.

Vleugel, J. and Janic, M. (2004) *Route Choice and the Impact of 'Logistic Routes.* Taniguchi, E. and Thompson, R. (Eds.) *Logistics Systems for Sustainable Cities.* Elsevier.

Wang, Q., and Holguin-Veras, J. (2008) Investigation on the Attributes Determining Trip Chaining Behavior in Hybrid Micro-Simulation Urban Freight Models. *Transportation Research Record: Journal of the Transportation Research Board,* 2066, 1-8.

Wang, X., Khattak, A. and Zhang, Y. (2013) Is Smart Growth Associated with Reductions in Carbon Dioxide Emissions? *Transportation Research Record: Journal of the Transportation Research Board*, 2375, 62-70.

Weidner, T., Knudson, B., Picado, R. and Hunt, J. (2009) Sensitivity Testing with the Oregon Statewide Integrated Model. *Transportation Research Record: Journal of the Transportation Research Board*, 2133, 109-122.

Xu, J., Hancock, K. L., Southworth, F. (2003) Dynamic Freight Traffic Simulation Providing Real-Time Information at the Proceedings of the Simulation Conference, 2(2), 1711–1719.

Yan, J. and Habib, M.A.(2011) *Developing a Transit Demand Forecasting Model for Halifax Regional Municipality*, Technical report, Dalhousie Transportation Collaboratory (DalTRAC), Dalhousie University at Nova Scotia

You, S. I. (2012) Methodology for Tour-Based Truck Demand Modeling. Doctoral Thesis, University of California.

You, S. I., and Ritchie, S. G. (2012). Tour behavior of clean drayage trucks in Southern California. *Proceedings of the 91st Annual Meeting of Transportation Research Board*, Washington, D. C., January 22-26

Ziomas, I. C., Suppan, P., Rappengluck, B., Balis, D., Tzoumaka, P., Melas, D, and Zerefos, C. S. (1995). A contribution to the study of photochemical smog in the greater Athens area. Beitrage zur Physik der Atmosphare-Contributions to Atmospheric Physics, 68(3), 191-204.

Appendices

Appendix A VDF Functions used in Halifax Transport Network Model

$$\text{VDF}\,1 = \left(\frac{\text{Length} * 60}{100}\right) * \left\{1 + \left(\frac{\text{volau} + \text{volad}}{4400}\right)^4\right\}$$

$$\text{VDF}\,2 = \left(\frac{\text{Length} * 60}{70}\right) * \left\{1 + \left(\frac{\text{volau} + \text{volad}}{3200}\right)^4\right\}$$

$$\text{VDF}\,3 = \left(\frac{\text{Length} * 60}{50}\right) * \left\{1 + \left(\frac{\text{volau} + \text{volad}}{2200}\right)^4\right\}$$

$$\text{VDF}\,4 = \frac{\text{Length} * 60}{40}$$

$$\text{VDF}\,5 = \frac{\text{Length} * 60}{30}$$

Here, Length= length of each link

volau= Auto equivalent traffic volume in the corresponding link

volad= Additional auto equivalent traffic volume in the corresponding link

Appendix B Trip Generation Model Results

Table B-1 Trip Production Regression Model Results

Variables	Parameter	T- stat
Constant	-1.3294	-11.65
Household Characteristics		
Employment rate	2.0765	41.25
Average Household Size	0.5145	37.02
Neighborhood characteristics		
Urban Core	0.0017	.10
Suburban	0.0292	2.12
Average individual income		
$15000-$30,000	0.0613	1.04
$30,000-$45000	0.1009	1.71
$45000-$60,000	0.0798	1.34
$60,000-$75000	0.0211	0.35
$75,000 and above	-0.0170	-0.23
Adjusted R –Sq	0.8731	

Table B-2 Trip Production and Attraction Summary for Work Trip

	Location	Work Trip Production	Work Trip Attraction
Urban Core	Halifax Core (South End)	6475	4915
	Halifax Core (Citadel-Downtown)	6099	57361
	Halifax Core (University-Residential)	7014	5286
	Halifax Core (Chebucto)	7204	7716
	Halifax Core (North End)	5833	7276
	Dartmouth Core (Dartmouth North)	6329	6720
	Dartmouth Core (Dartmouth South)	6886	13537
	Total Urban	**45840**	**102811**
Suburban	Halifax (Armdale)	12139	5053
	Halifax (Fairview Clayton park)	20827	8824
	St Margaret's Bay	3700	1835
	Bedford Core	10603	5595
	Bedford	1468	1006
	Sackville	14662	8200
	Dartmouth North	11655	27857
	Dartmouth South	12437	6614
	Cole Harbor Eastern Passage	14495	3627
	Total Suburban	**101986**	**68611**
Rural	Prospect	7692	5279
	St. Margarets Bay	5075	2434
	Sackvile	17276	6929
	Waverley-fall River	2820	2667
	Portar's Lake-Lawraencetown	9652	5132
	Musquo-doboit Harbour	5496	2457
	Sheet Harbour	1521	1037
	Total Rural	**49532**	**25935**

Appendix C Modal Split Results

Table C-1 Travel Time Regression Model for Modal Split

	Auto Driver		Auto Passenger		Transit		Bike		Walk	
Variable	Param eter	T-stat	Param eter	T-stat	Param eter	T-stat	Param eter	T-stat	Param eter	T-stat
Constant	22.87	8.45	24.03	8.93	24.3	1.25	4.75	0.51	-31.5	-2.83
Distance (KM)	.5645	11.65	.5292	11.34	.737	4.18	1.844	2.7	6.963	7.86
Suburban	-8.36	-3.61	-8.16	-3.55	14.1	0.81				
Urban	-11.57	-3.93	-10.47	-2.93	16.8	0.91	-1.22	-0.4	14.68	2.42
Distance <5km	-5.35	-2.02	2.20	0.52	-17.78	-2.34	4.12	0.56	21.64	3.31
Distance 5km to 10km	-0.40	-0.20	1.01	0.48	-8.10	-1.14	4.94	1		
R-Sq (adj)	0.7408		0.6856		0.5669		0.5107		0.5651	

Appendix D Sample of Standard Multiclass Traffic Assignment

HRM

1 – multiclass assignment

INRO - Emme Standard - Data management - Scenario

Scenario 1 —*multiclass assignment*

Status for scenario:

1 – multiclass assign

About This Network

6 modes

222 centroids

2237 regular nodes

5272 directional links

1 transit vehicle types

27 transit lines

1604 transit line segments

507 turns

Write protected: False

Delete protected: False

Traffic Assignment

Standard traffic assignment

Open the Modeller Logbook to this entry

Namespace	inro.emme.traffic_assignment.standard_traffic_assignment
Used from	Modeller Session
Start time	2018-11-03 23:04:28
End time	2018-11-03 23:04:30
Error	None

Extra function parameters

- el1 =
- el2 =
- el3 =
- ep1 =
- ep2 =
- ep3 =

Class specification

1. Mode: a - 'Passen Car' on 5264 links, AUTO
   Demand: mf1 car - 'OD_Passenger Car'
   Generalized cost:
   - Link costs: ul1
   - Perception factor: 1

   Results:
   - O-D travel times:
     - Shortest paths: mf5 TT_Car - 'Travel Time_Passenger Car'
   - Link volumes: @c1
2. Mode: d - 'ligt truck' on 3548 links, AUX_AUTO
   Demand: mf2 LT - 'OD_Light Truck'

Generalized cost:

- Link costs: ul2
- Perception factor: 1

Results:

- O-D travel times:
    - Shortest paths: mf6 TT_LT - 'Travel Time_Light Truck'
- Link volumes: @t2

3. Mode: e - 'med truck' on 3527 links, AUX_AUTO

   Demand: mf3 MT - 'OD_Medium Truck'

   Generalized cost:

   - Link costs: ul2
   - Perception factor: 1

   Results:

   - O-D travel times:
       - Shortest paths: mf7 TT_MT - 'Travel Time_Medium Truck'
   - Link volumes: @t3

4. Mode: f - 'hvy truck' on 3527 links, AUX_AUTO

   Demand: mf4 HT - 'OD_Heavy Truck'

   Generalized cost:

   - Link costs: ul3
   - Perception factor: 1

   Results:

   - O-D travel times:
       - Shortest paths: mf8 TT_HT - 'Travel Time_Heavy Truck'
   - Link volumes: @t4

Stopping criteria

- Max iterations: 100
- Best relative gap: 0.1%
- Normalized gap: 0.05
- Relative gap: 0

Performance settings

- Number of processors: max

Report

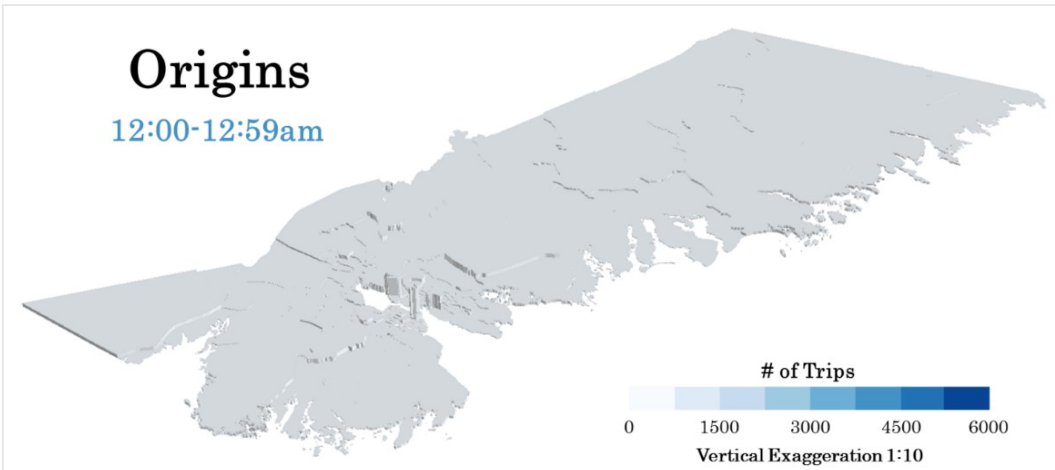
- Stopping criterion: BEST_RELATIVE_GAP
- Number of iterations: 16
- Relative gap: 0.00137063
- Best relative gap: 0.0861%
- Normalized gap: 25.912994

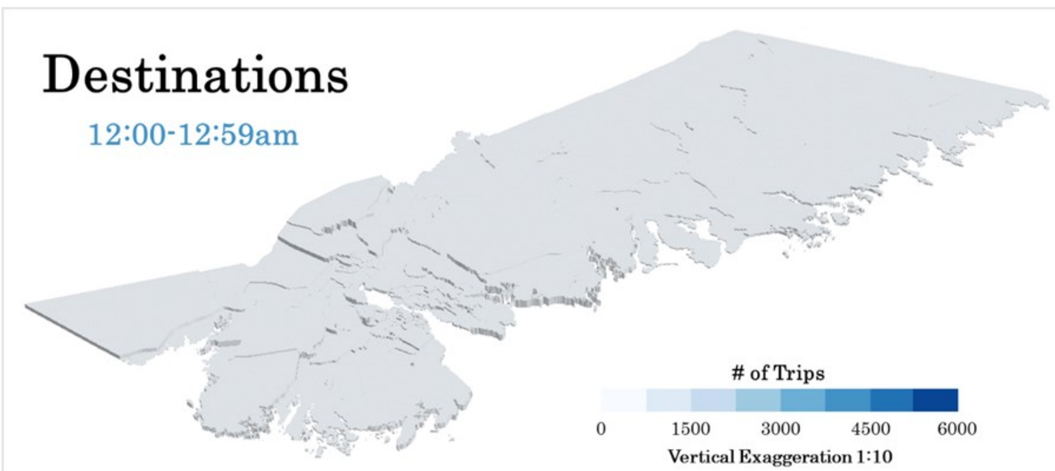
Transit Assignment

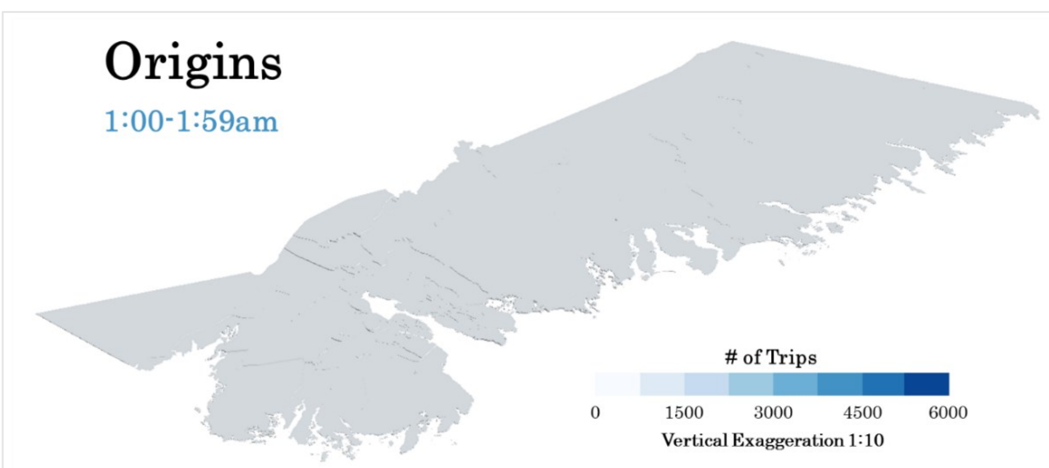
There are no transit assignment results in this scenario.

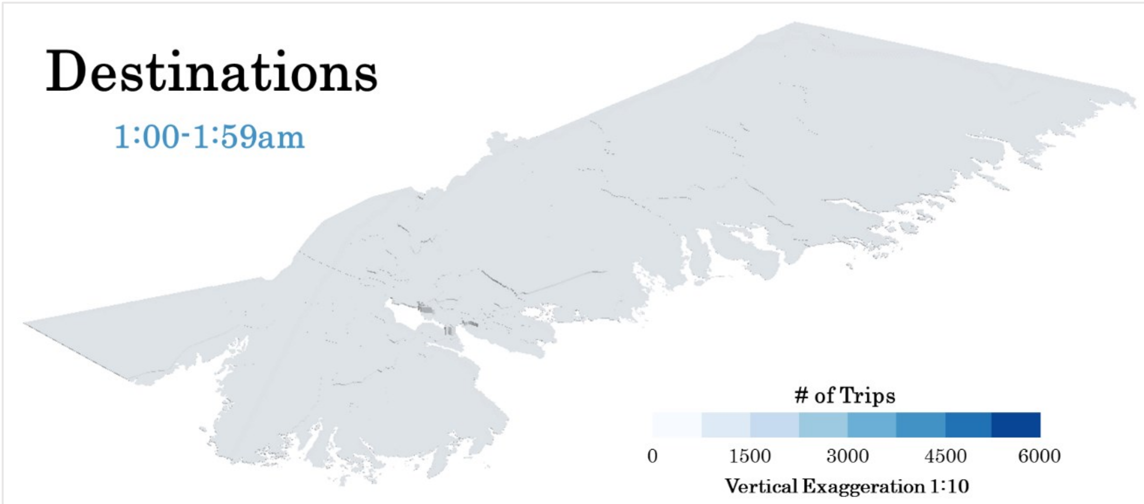
INRO

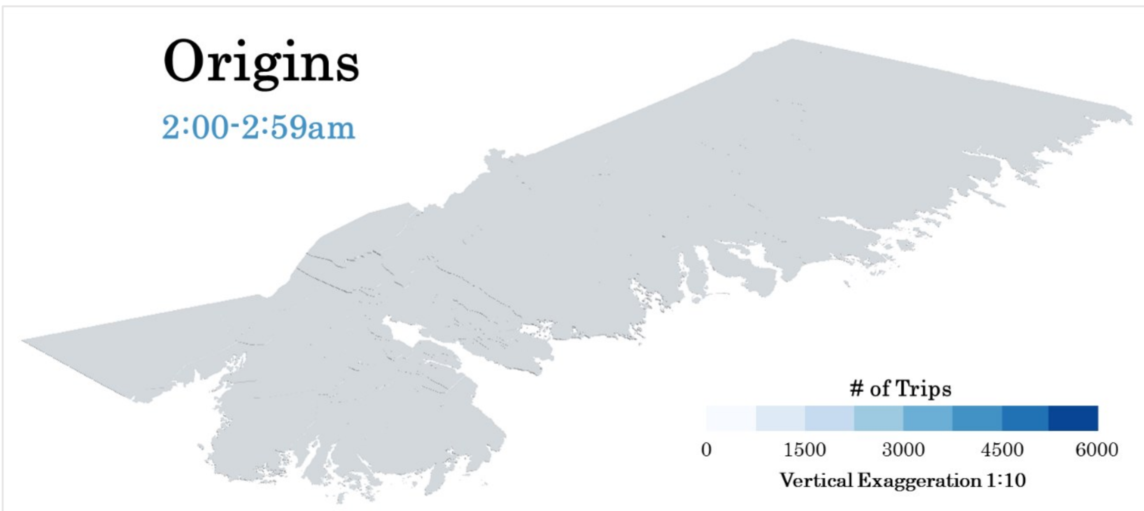
Appendix E 24-hour Origin-Destination for the Model Year of 2011

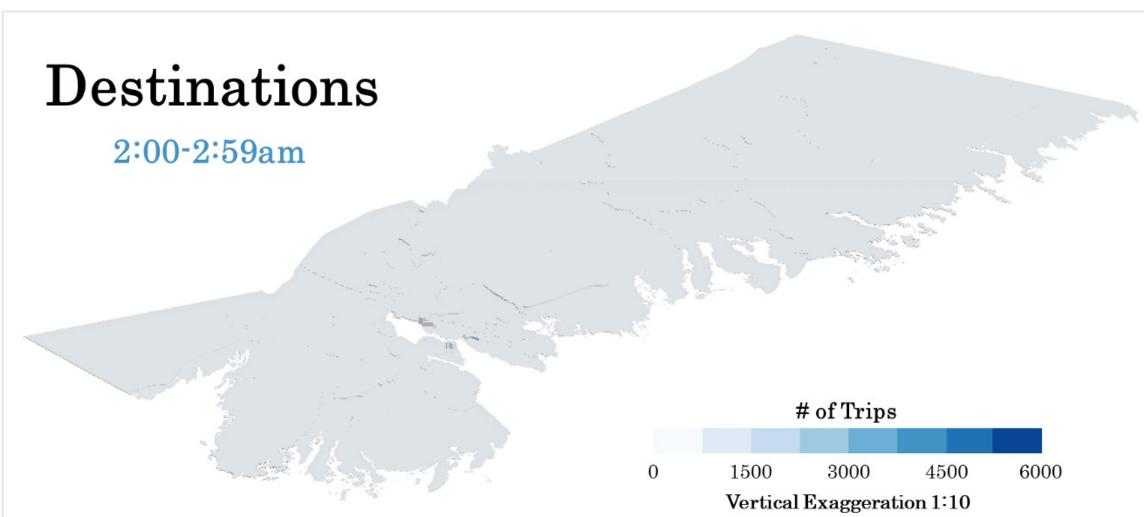


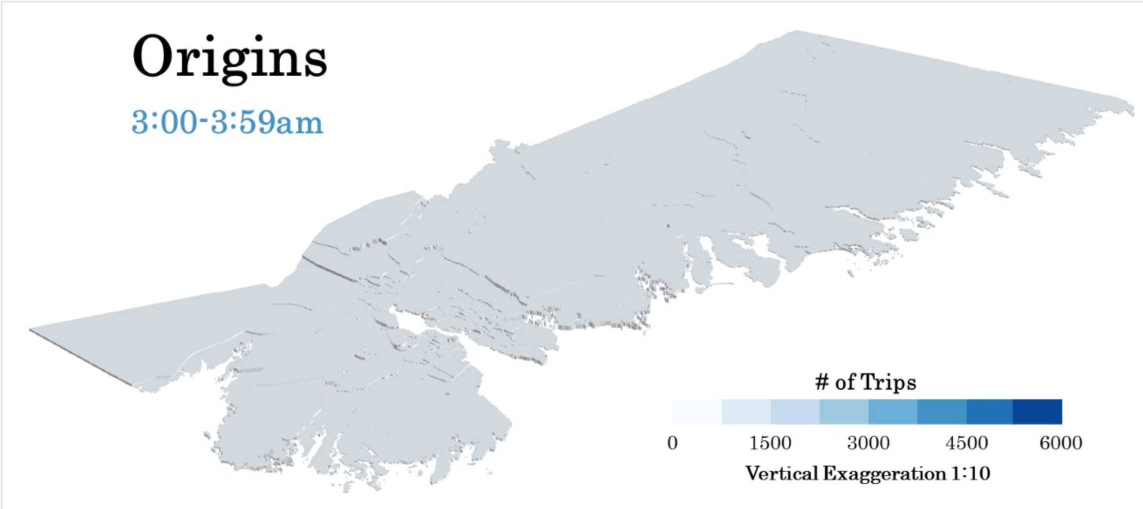


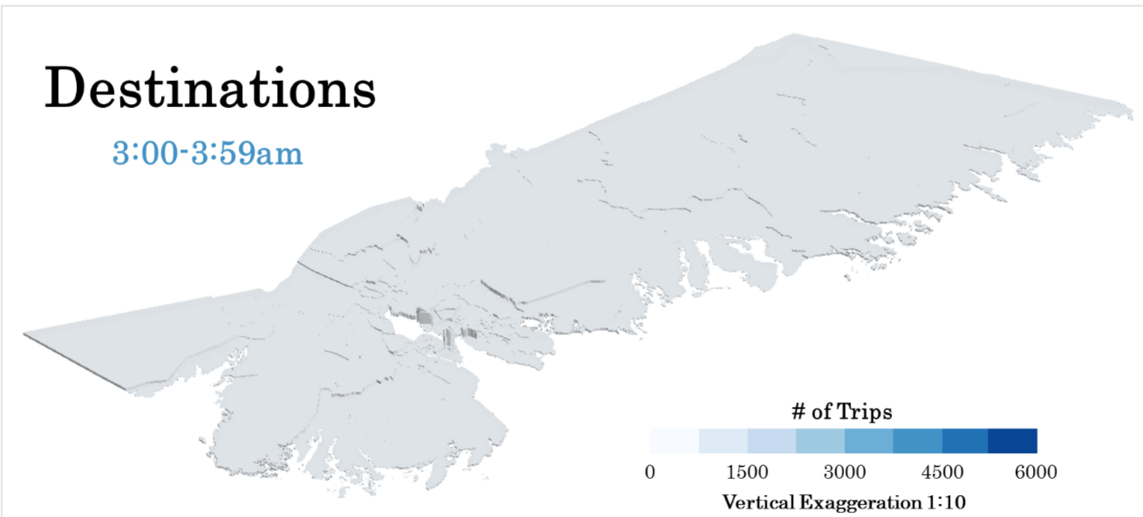


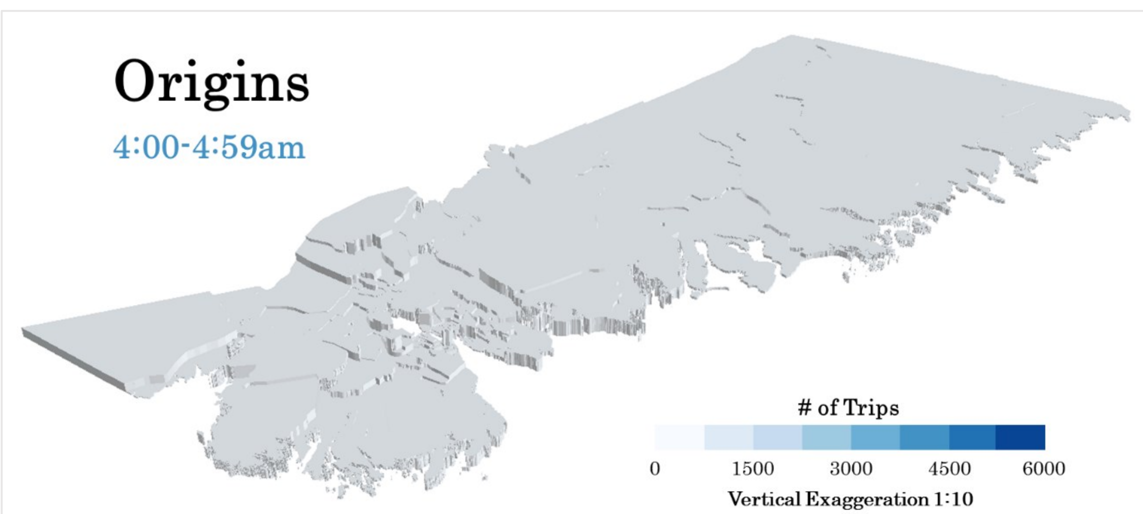

Destinations
1:00-1:59am
# of Trips
0
1500
3000
4500
6000
Vertical Exaggeration 1:10

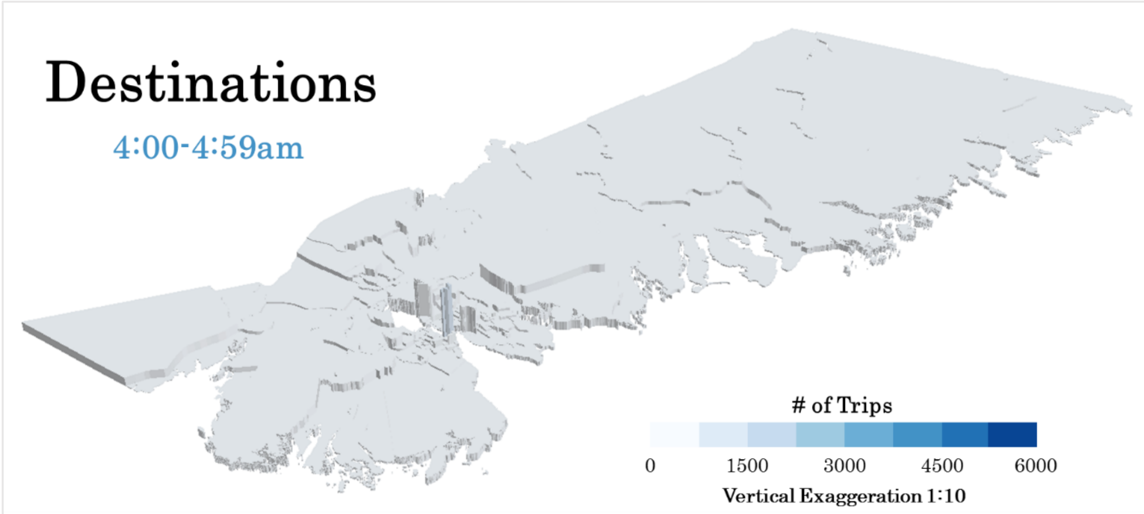

Origins
2:00-2:59am
# of Trips
0
1500
3000
4500
6000
Vertical Exaggeration 1:10

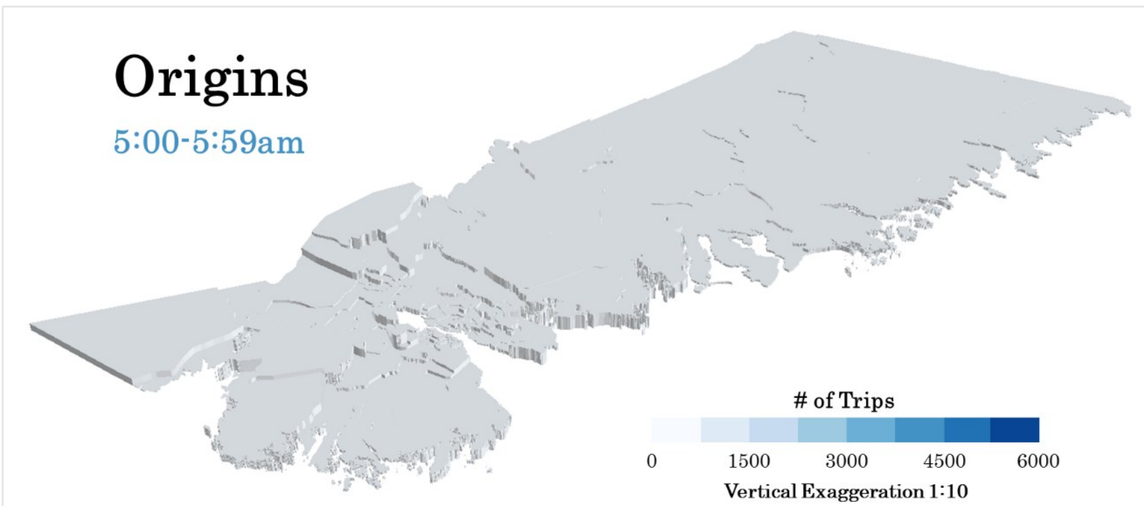

Destinations
2:00-2:59am
# of Trips
0
1500
3000
4500
6000
Vertical Exaggeration 1:10

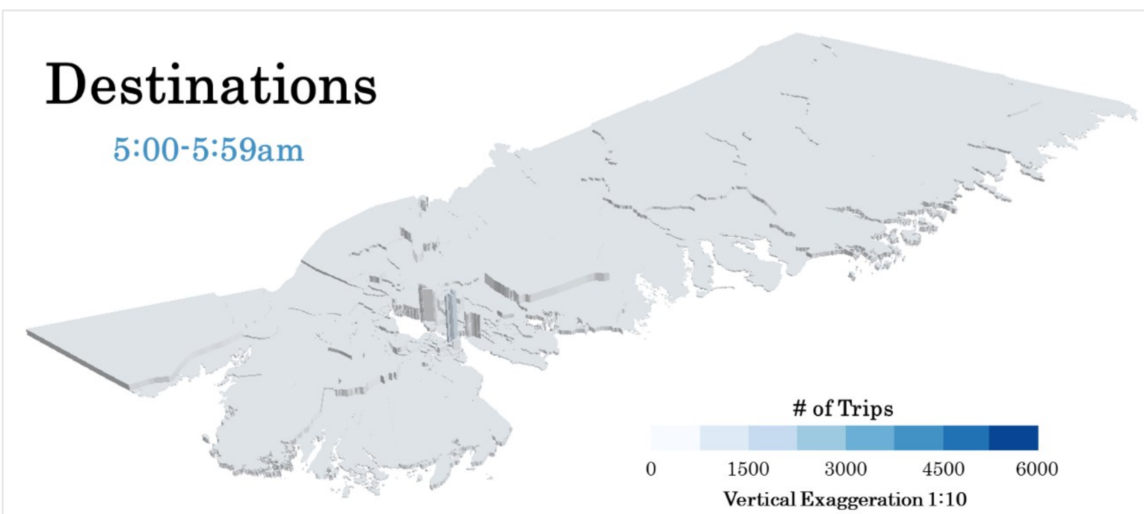

Origins
3:00-3:59am
# of Trips
0
1500
3000
4500
6000
Vertical Exaggeration 1:10

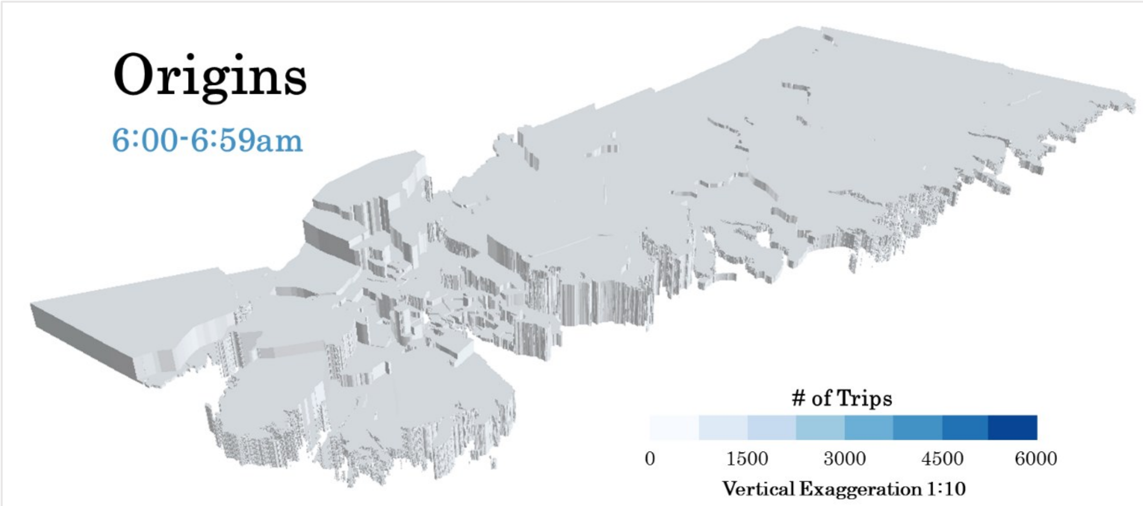

Destinations
3:00-3:59am
# of Trips
0
1500
3000
4500
6000
Vertical Exaggeration 1:10

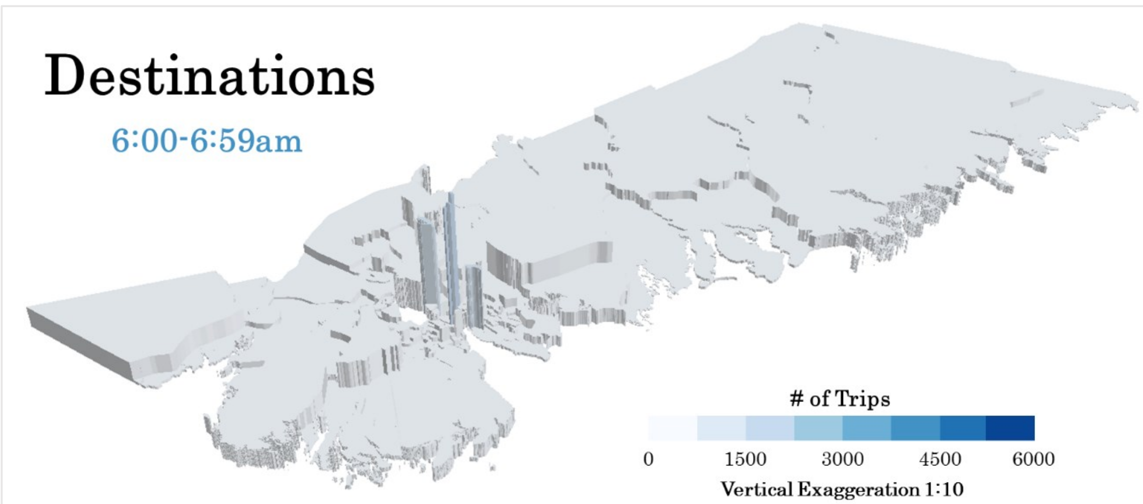

Origins
4:00-4:59am
# of Trips
0
1500
3000
4500
6000
Vertical Exaggeration 1:10

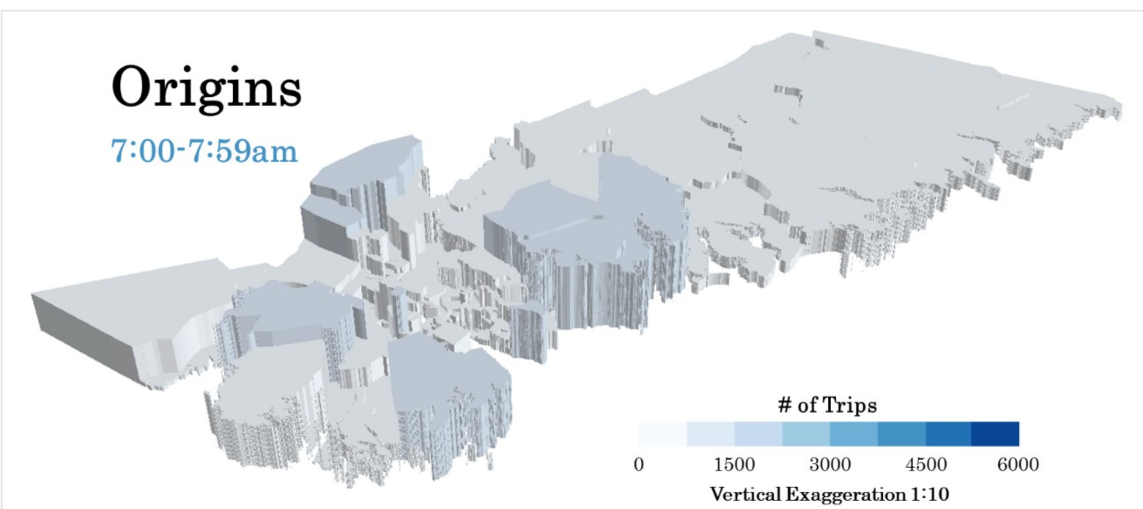

Destinations
4:00-4:59am
# of Trips
0
1500
3000
4500
6000
Vertical Exaggeration 1:10

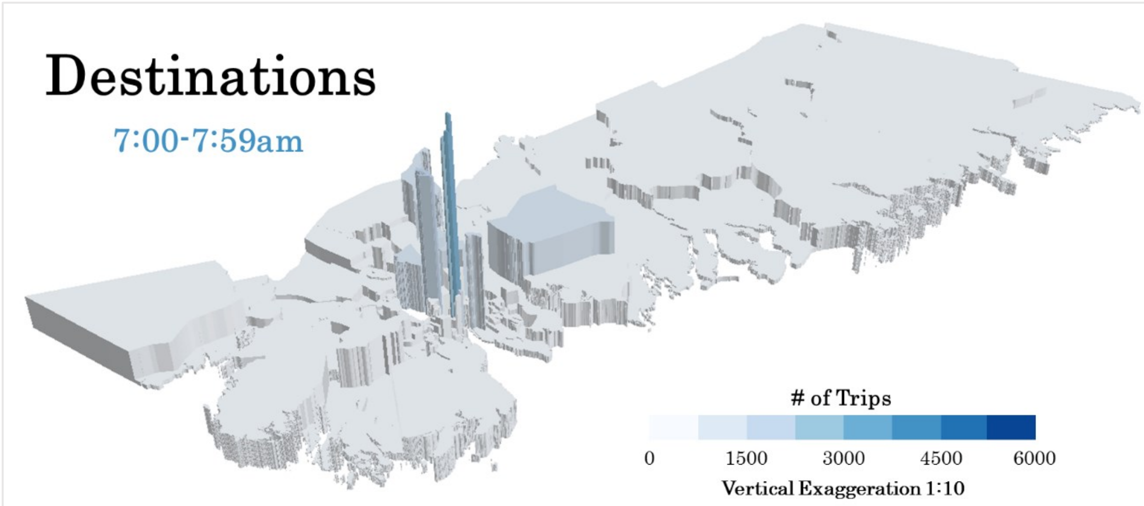

Origins
5:00-5:59am
# of Trips
0
1500
3000
4500
6000
Vertical Exaggeration 1:10

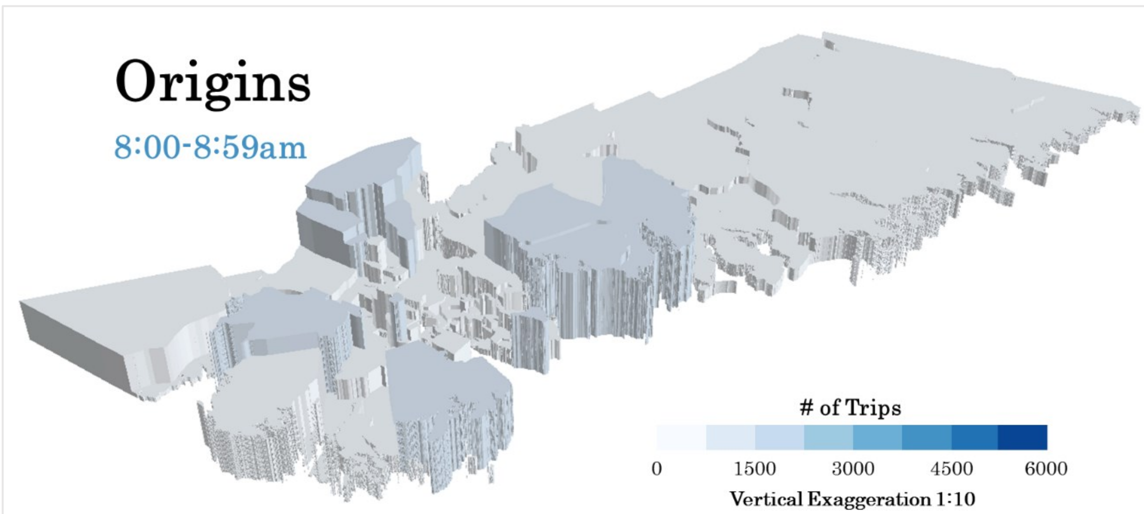

Destinations
5:00-5:59am
# of Trips
0
1500
3000
4500
6000
Vertical Exaggeration 1:10

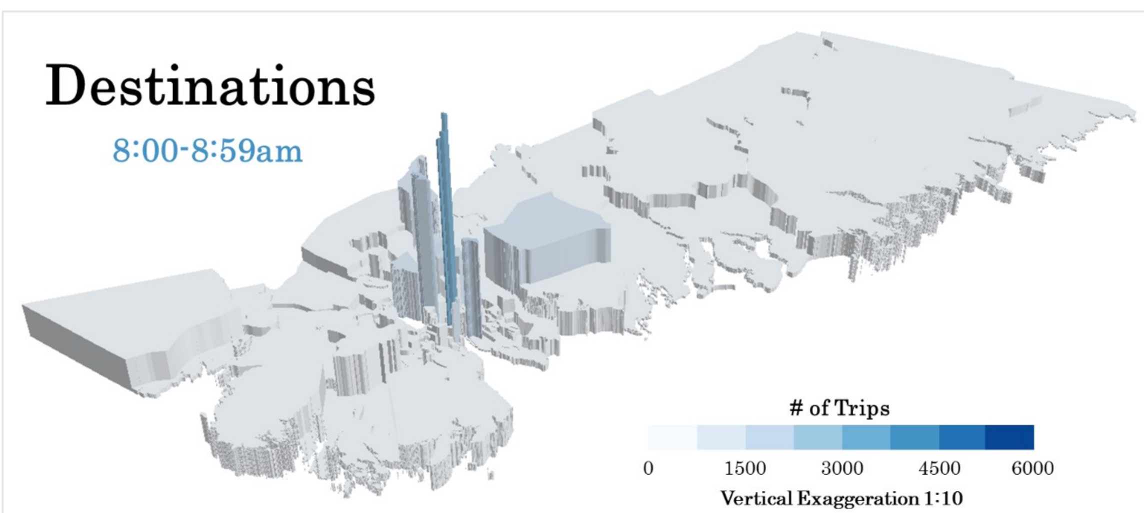

Origins
6:00-6:59am
# of Trips
0
1500
3000
4500
6000
Vertical Exaggeration 1:10

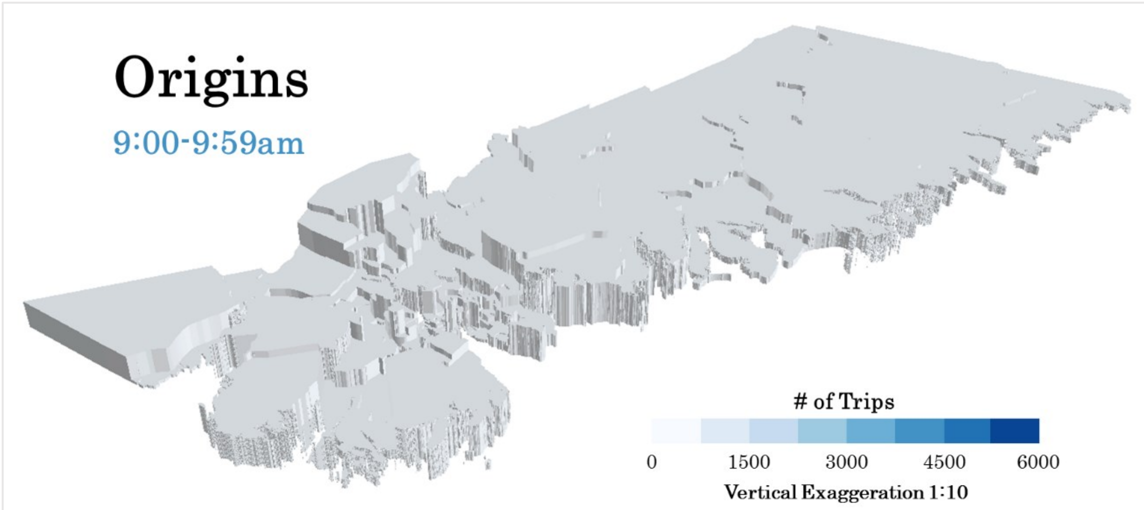

Destinations
6:00-6:59am
# of Trips
0
1500
3000
4500
6000
Vertical Exaggeration 1:10

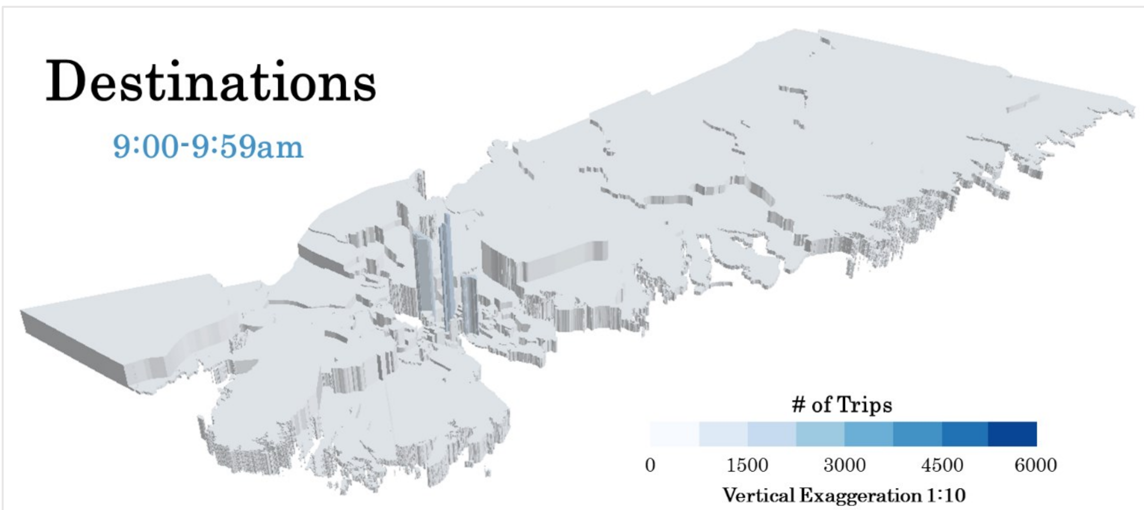

Origins
7:00-7:59am
# of Trips
0
1500
3000
4500
6000
Vertical Exaggeration 1:10

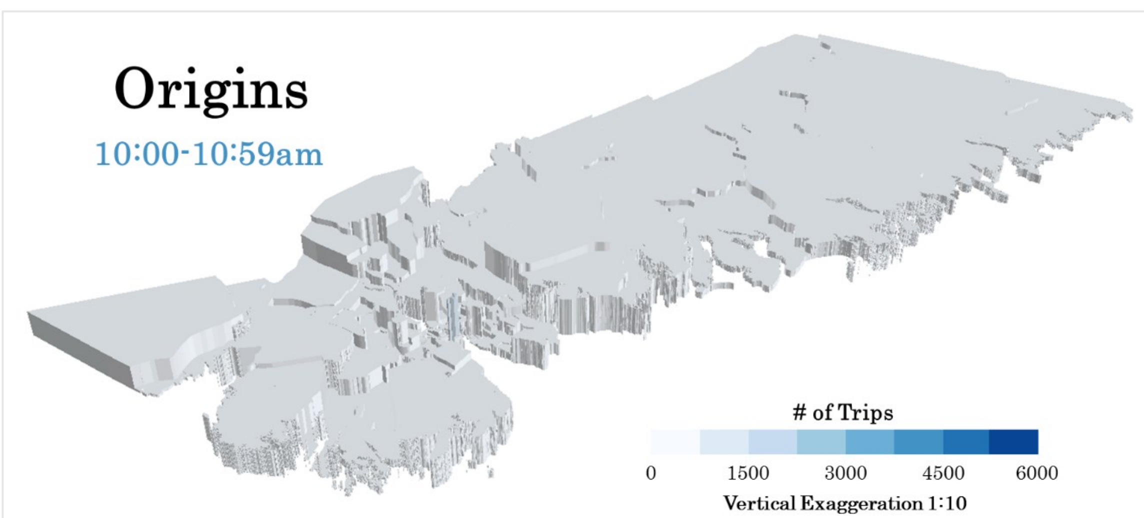

Destinations
7:00-7:59am
# of Trips
0
1500
3000
4500
6000
Vertical Exaggeration 1:10

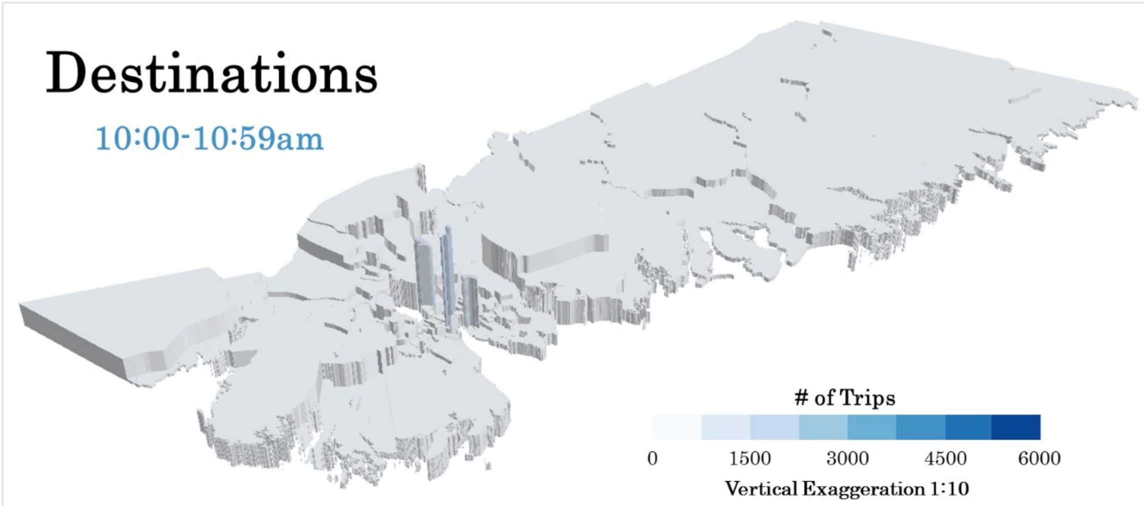

Origins
8:00-8:59am
# of Trips
0
1500
3000
4500
6000
Vertical Exaggeration 1:10

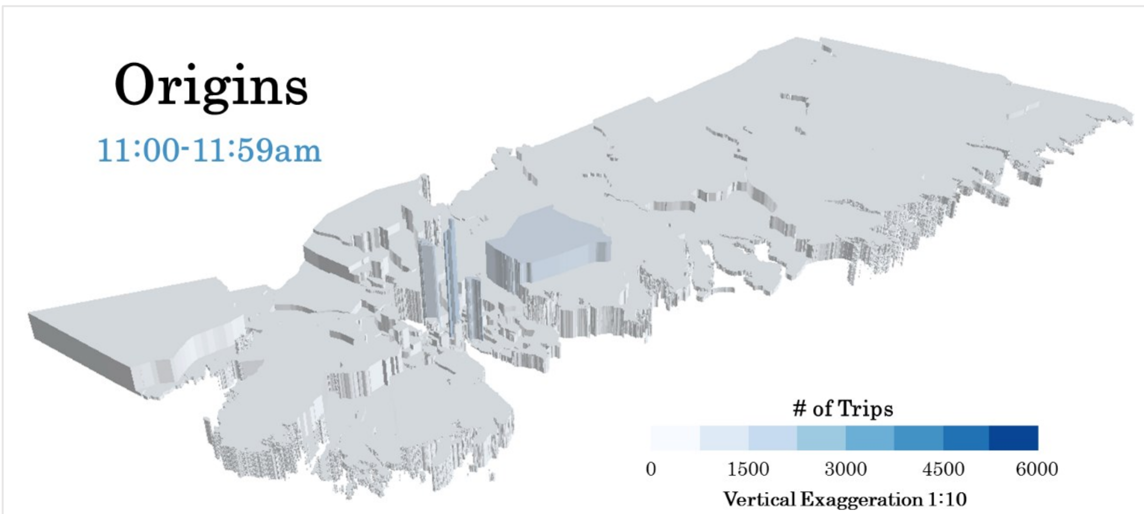

Destinations
8:00-8:59am
# of Trips
0
1500
3000
4500
6000
Vertical Exaggeration 1:10

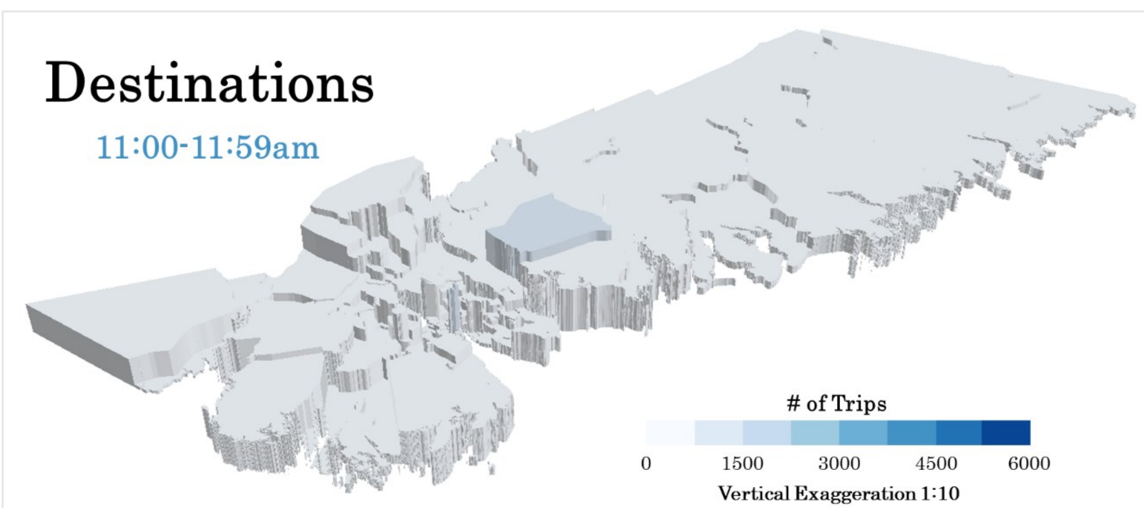

Origins
9:00-9:59am
# of Trips
0
1500
3000
4500
6000
Vertical Exaggeration 1:10

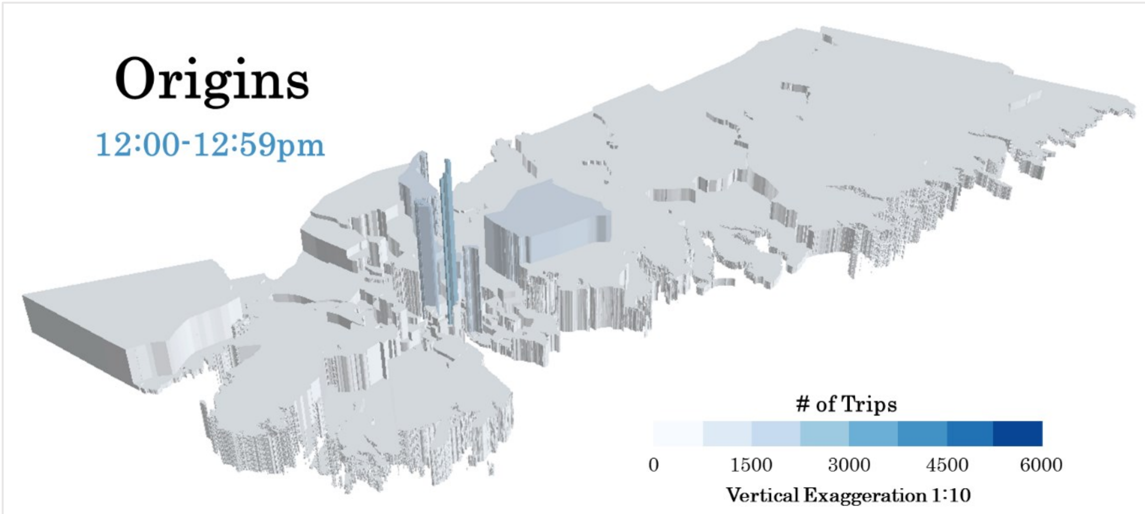

Destinations
9:00-9:59am
# of Trips
0
1500
3000
4500
6000
Vertical Exaggeration 1:10

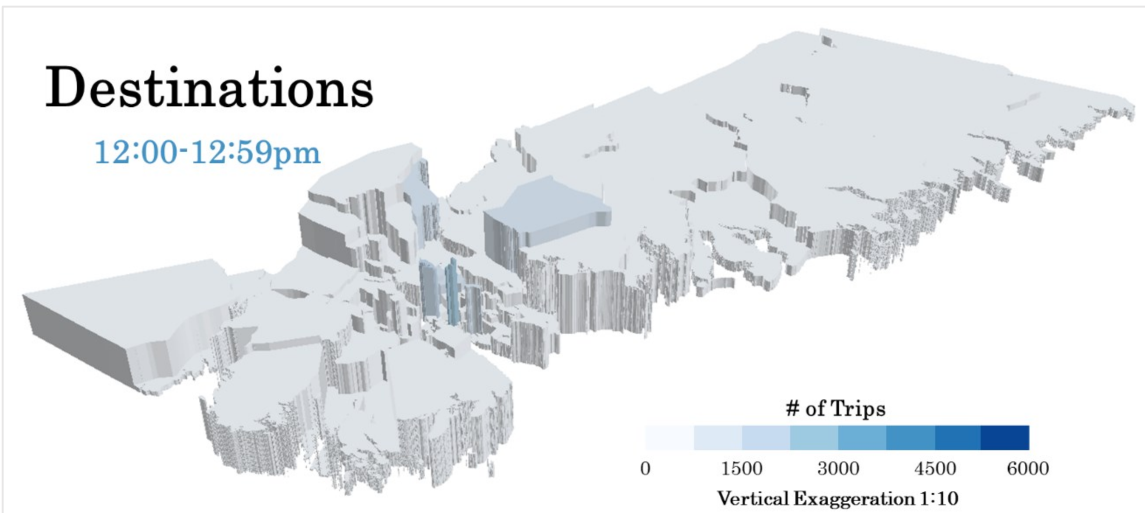

Origins
10:00-10:59am
# of Trips
0
1500
3000
4500
6000
Vertical Exaggeration 1:10

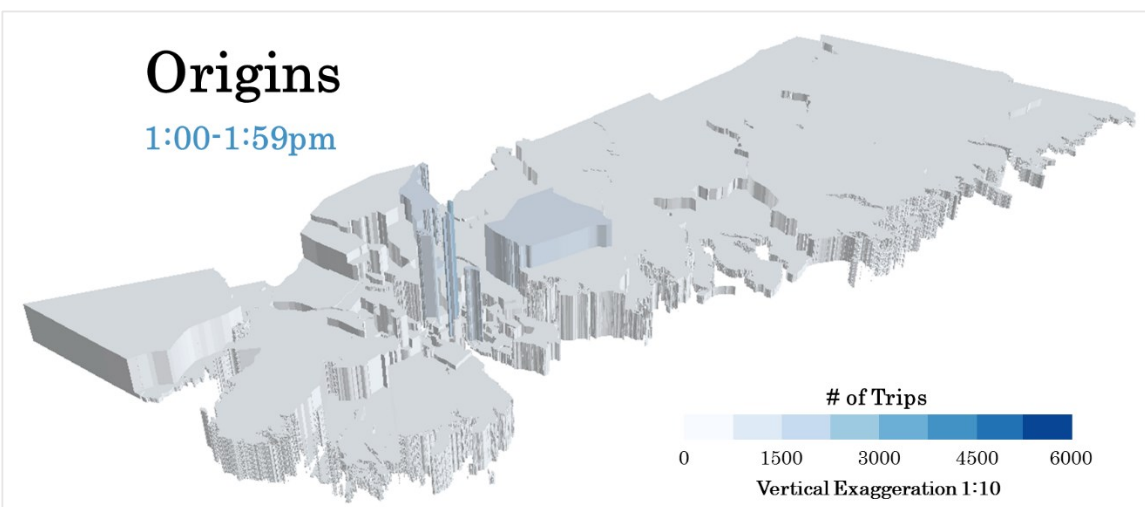

Destinations
10:00-10:59am
# of Trips
0
1500
3000
4500
6000
Vertical Exaggeration 1:10

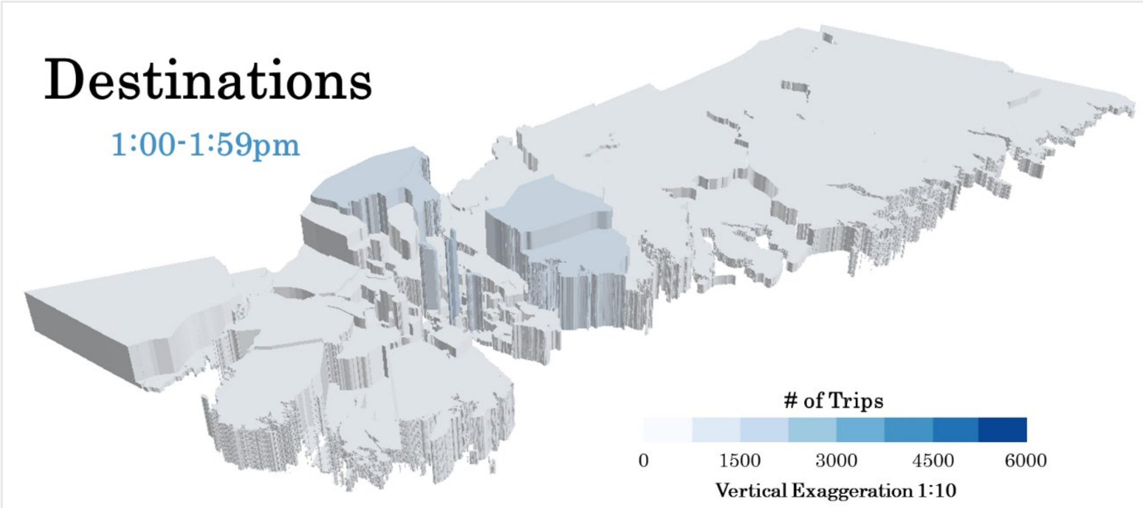

Origins
11:00-11:59am
# of Trips
0
1500
3000
4500
6000
Vertical Exaggeration 1:10

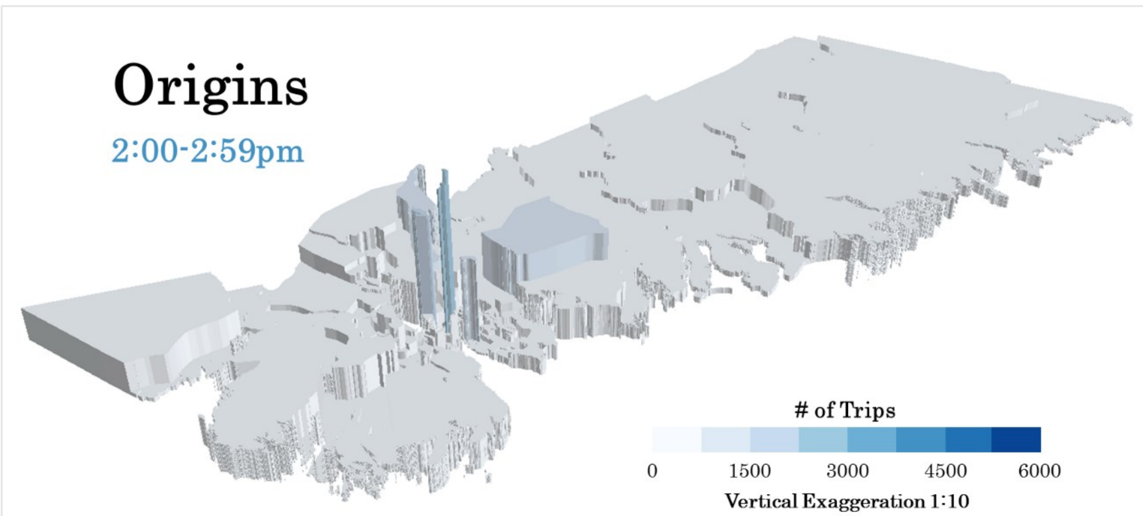

Destinations
11:00-11:59am
# of Trips
0
1500
3000
4500
6000
Vertical Exaggeration 1:10

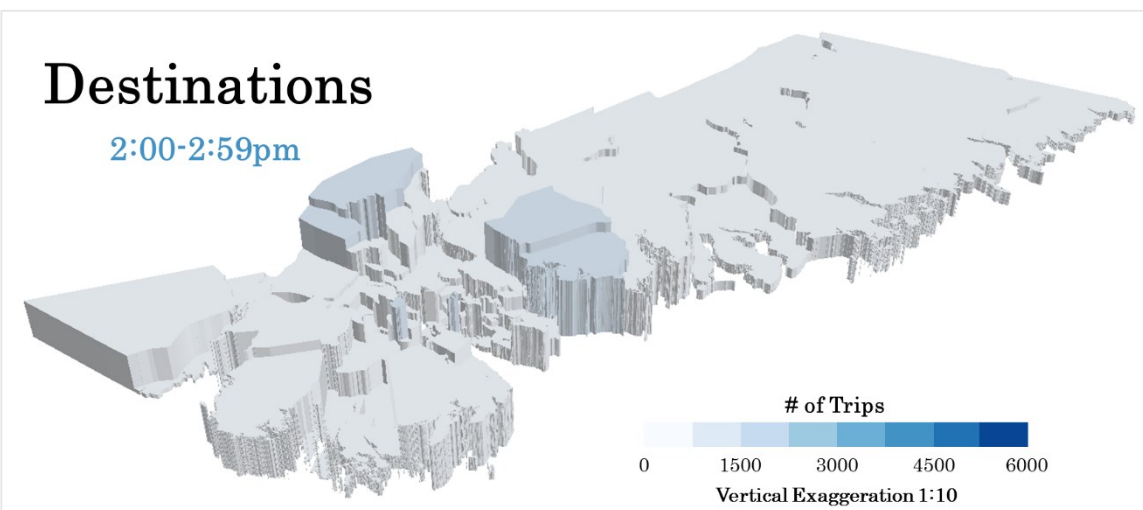

Origins
12:00-12:59pm
# of Trips
0
1500
3000
4500
6000
Vertical Exaggeration 1:10

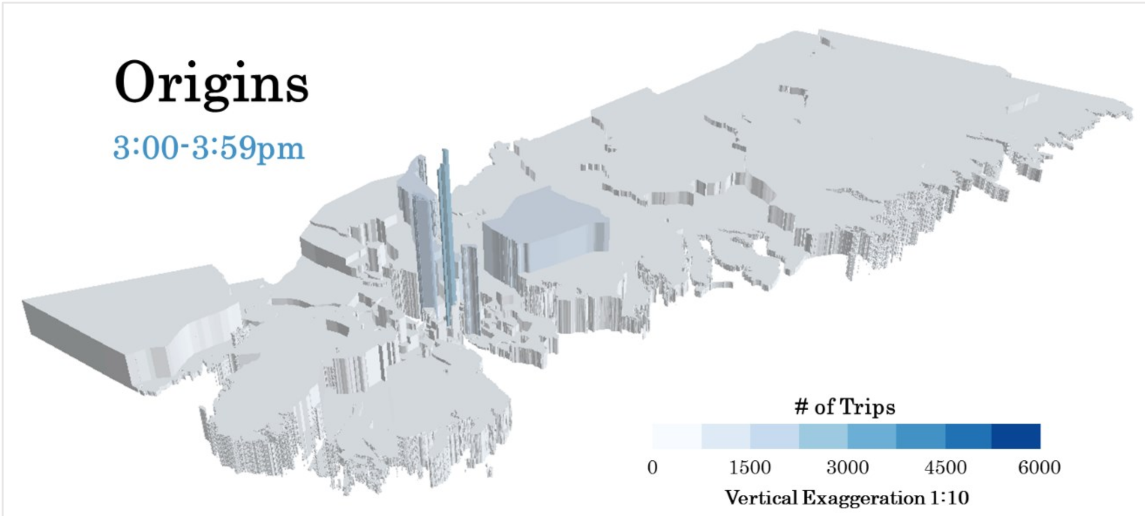

Destinations
12:00-12:59pm
# of Trips
0
1500
3000
4500
6000
Vertical Exaggeration 1:10

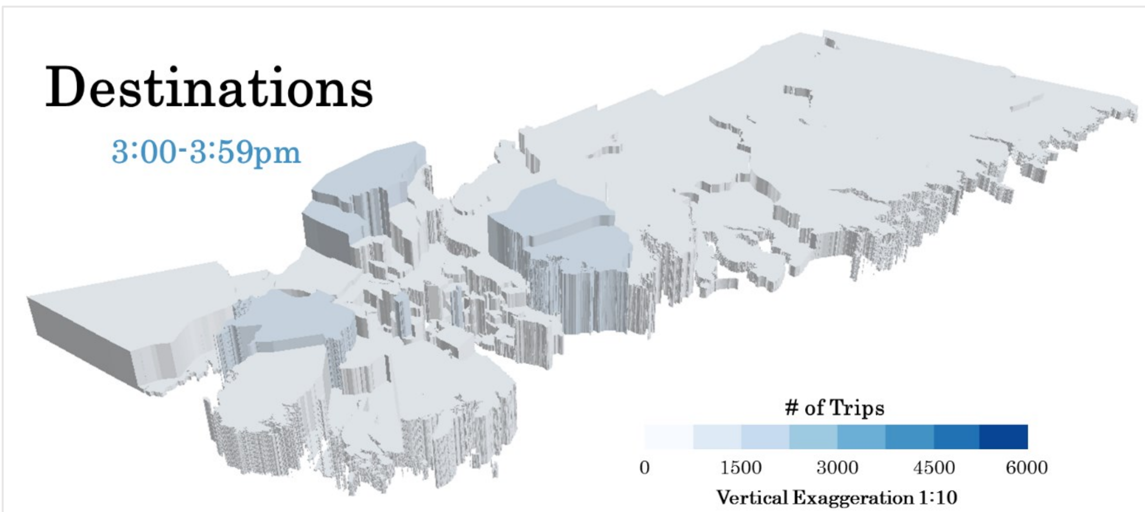

Origins
1:00-1:59pm
# of Trips
0
1500
3000
4500
6000
Vertical Exaggeration 1:10

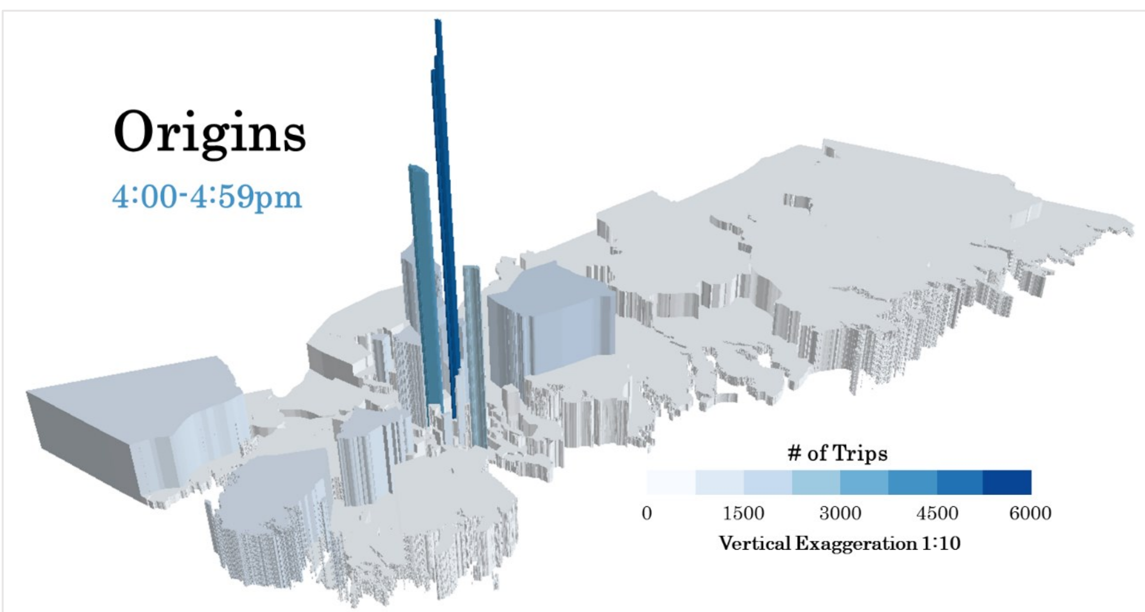

Destinations
1:00-1:59pm
# of Trips
0
1500
3000
4500
6000
Vertical Exaggeration 1:10

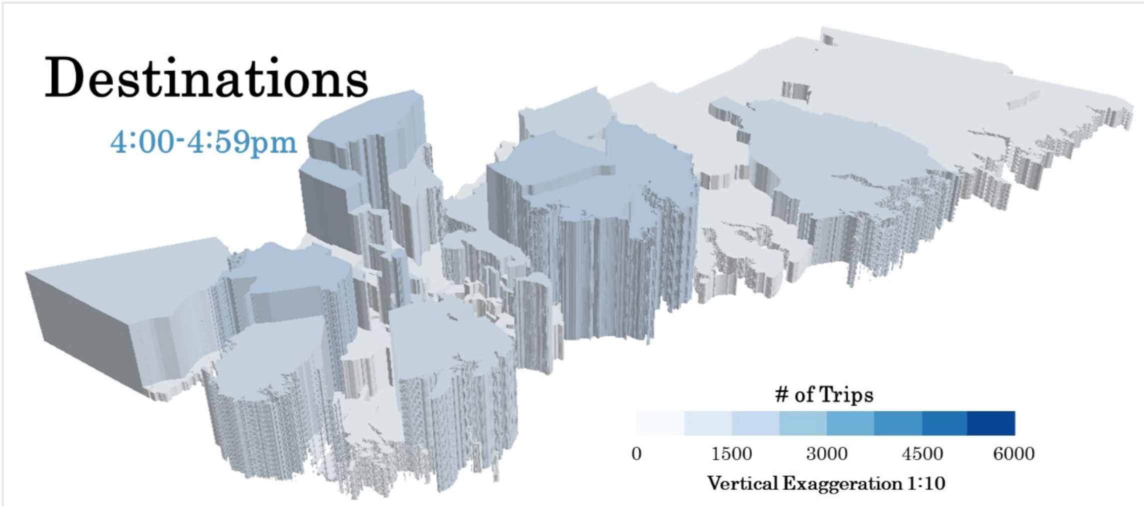

Origins
2:00-2:59pm
# of Trips
0
1500
3000
4500
6000
Vertical Exaggeration 1:10

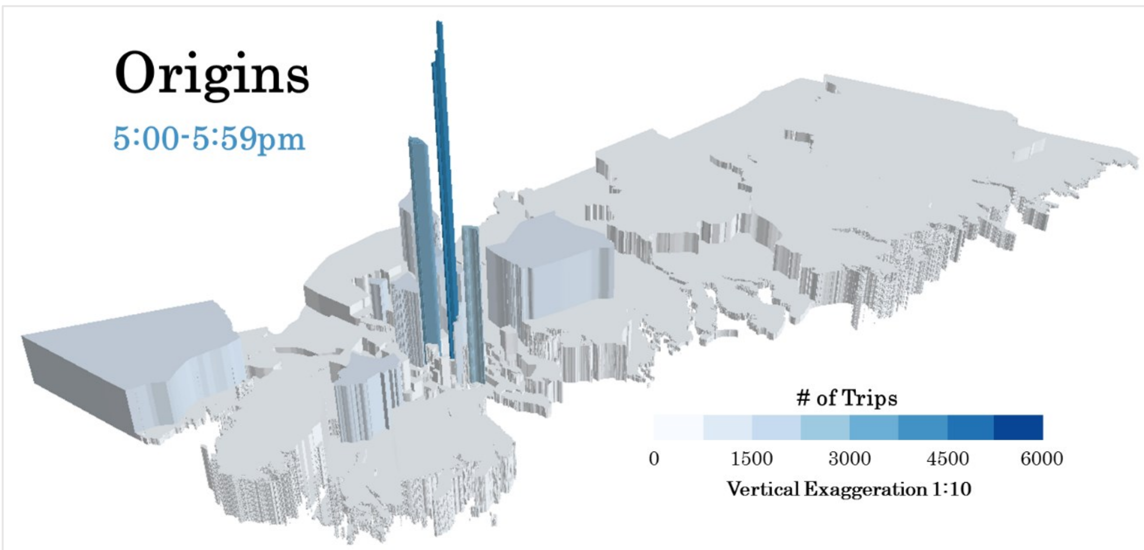

Destinations
2:00-2:59pm
# of Trips
0
1500
3000
4500
6000
Vertical Exaggeration 1:10

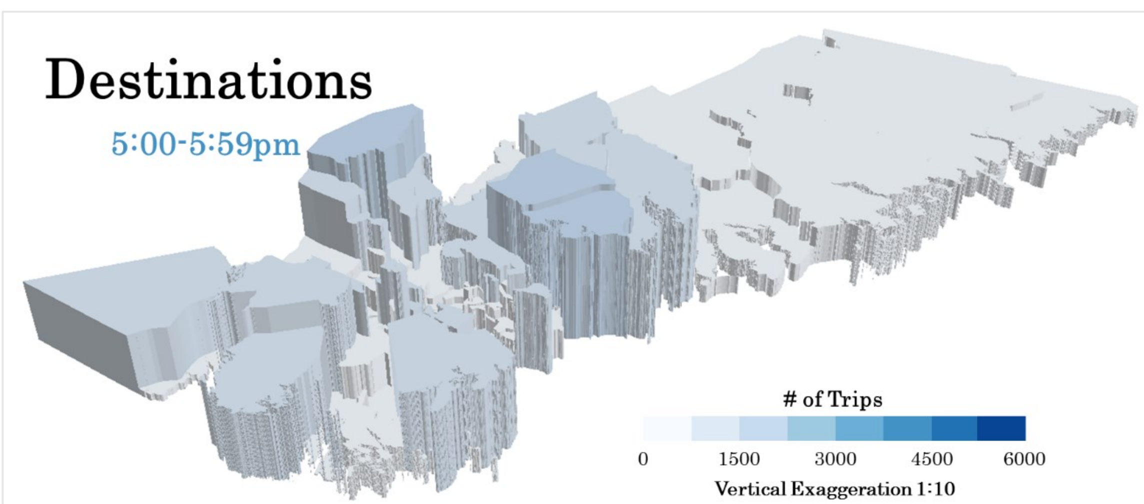

Origins
3:00-3:59pm
# of Trips
0
1500
3000
4500
6000
Vertical Exaggeration 1:10

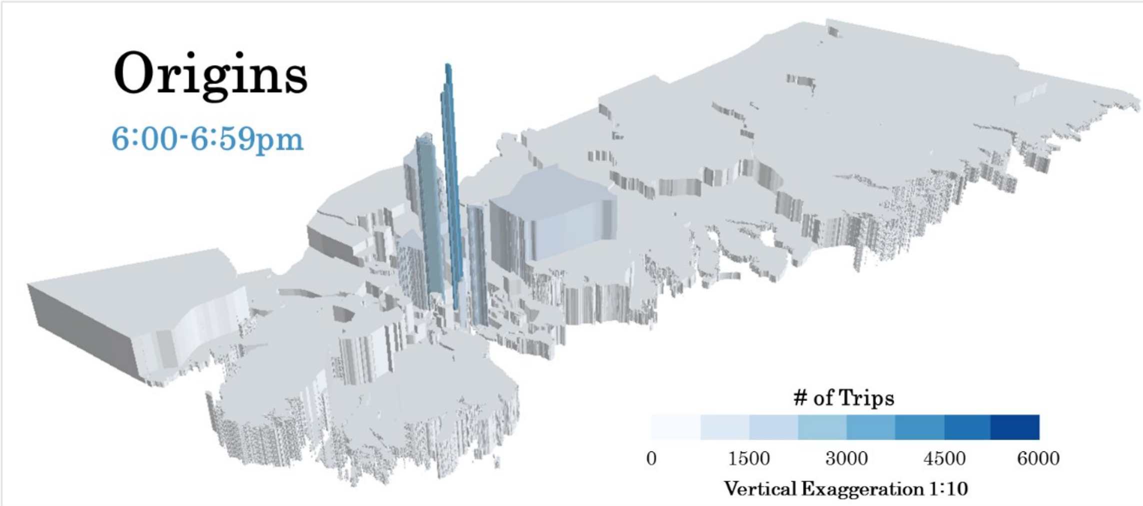

Destinations
3:00-3:59pm
# of Trips
0
1500
3000
4500
6000
Vertical Exaggeration 1:10

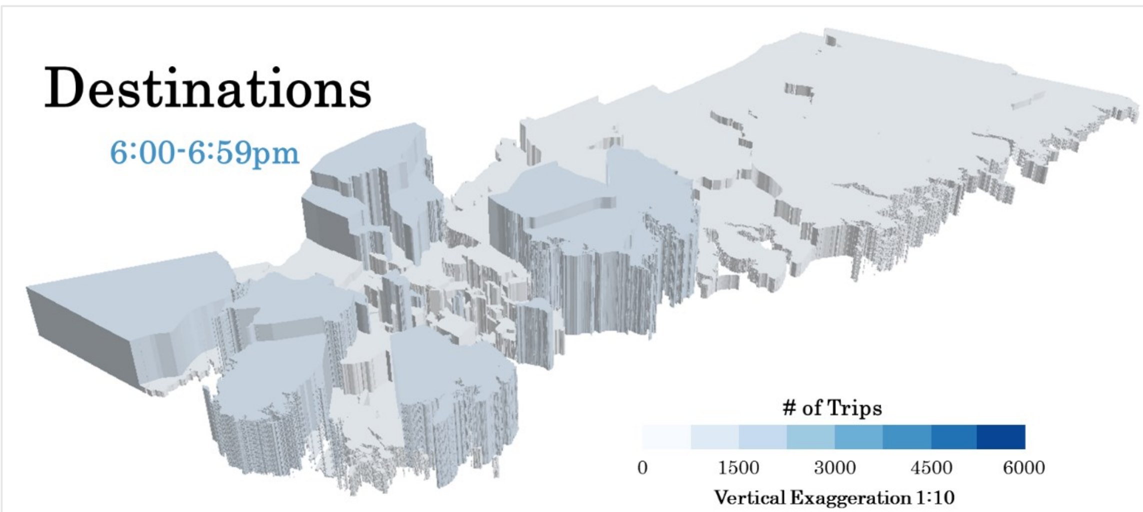

Origins
4:00-4:59pm
# of Trips
0
1500
3000
4500
6000
Vertical Exaggeration 1:10

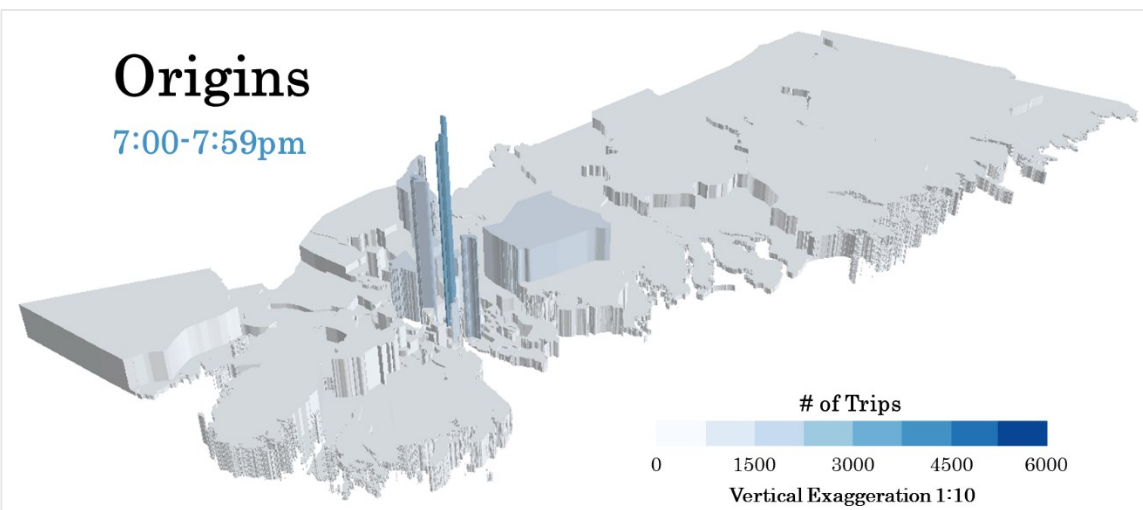

Destinations
4:00-4:59pm
# of Trips
0
1500
3000
4500
6000
Vertical Exaggeration 1:10

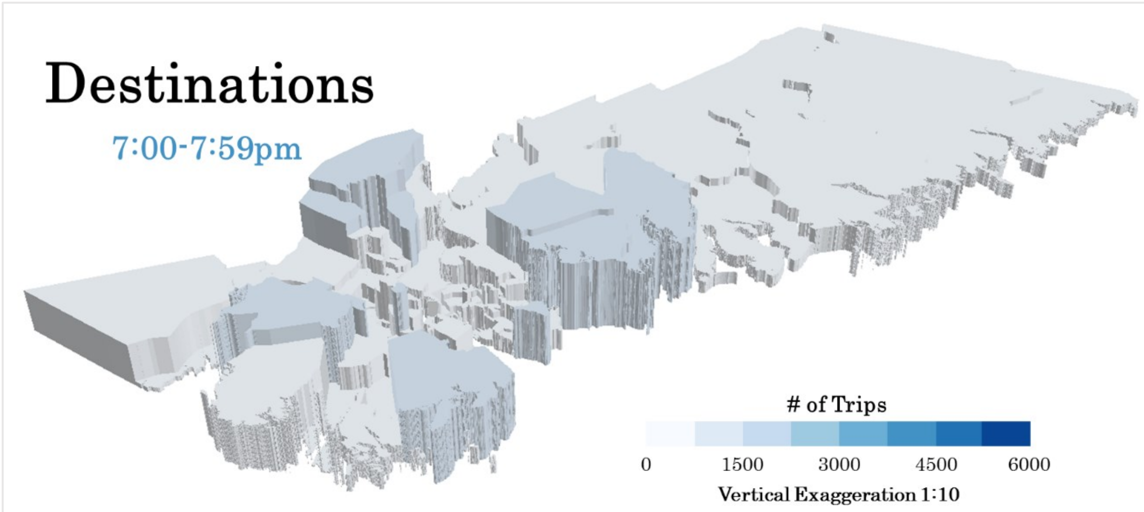

Origins
5:00-5:59pm
# of Trips
0
1500
3000
4500
6000
Vertical Exaggeration 1:10

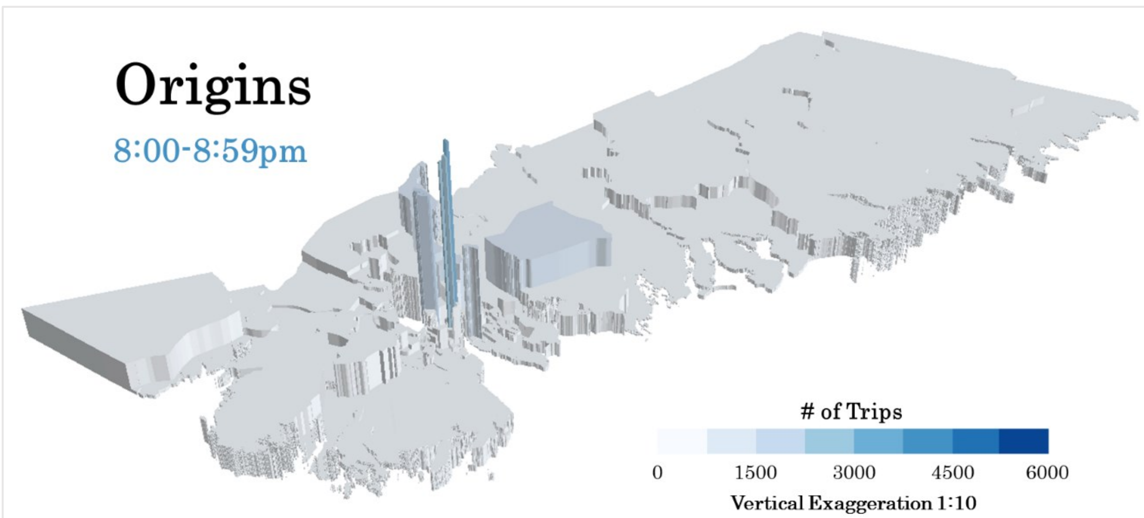

Destinations
5:00-5:59pm
# of Trips
0
1500
3000
4500
6000
Vertical Exaggeration 1:10

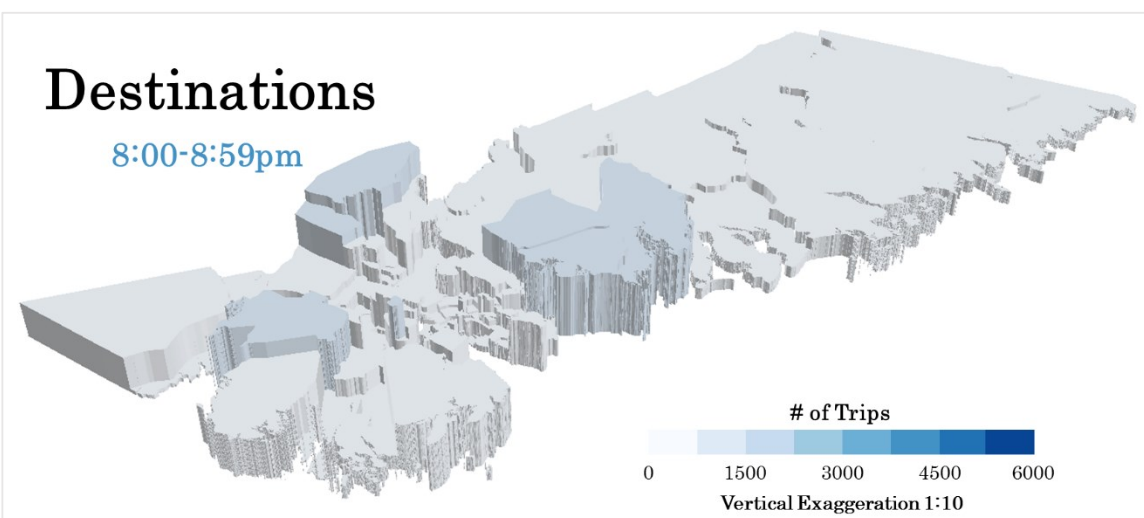

Origins
6:00-6:59pm
# of Trips
0
1500
3000
4500
6000
Vertical Exaggeration 1:10

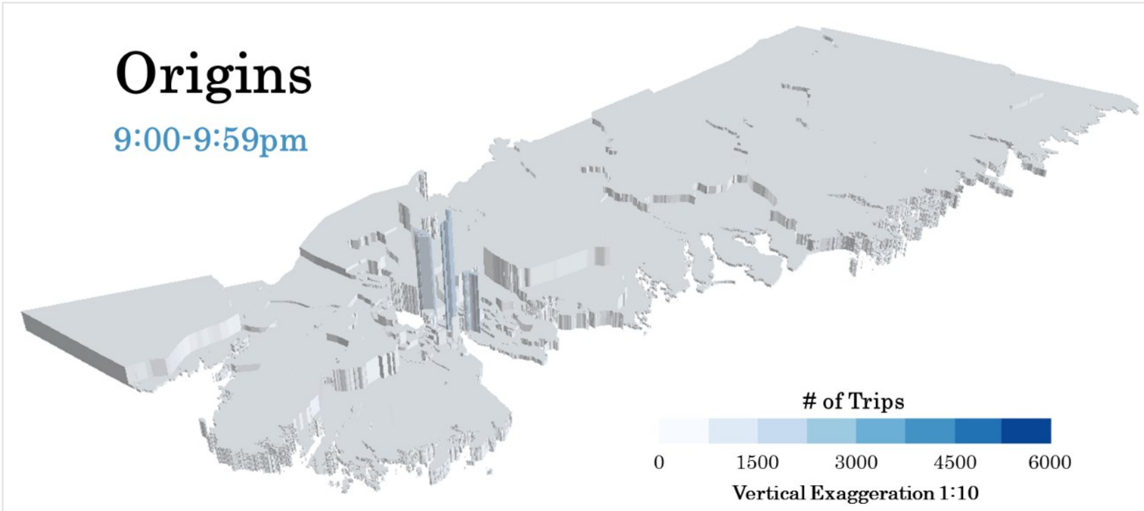

Destinations
6:00-6:59pm
# of Trips
0
1500
3000
4500
6000
Vertical Exaggeration 1:10

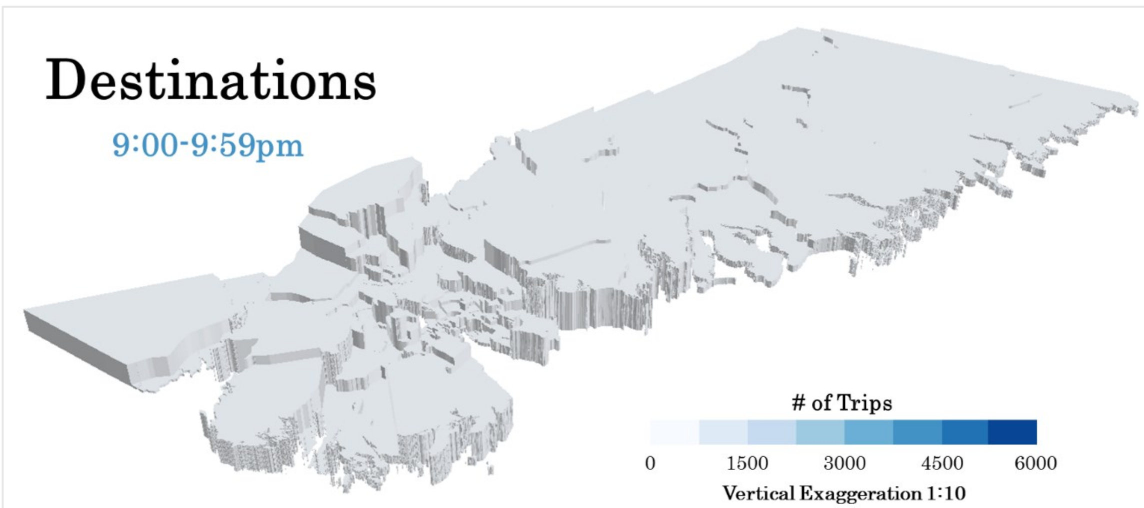

Origins
7:00-7:59pm
# of Trips
0
1500
3000
4500
6000
Vertical Exaggeration 1:10

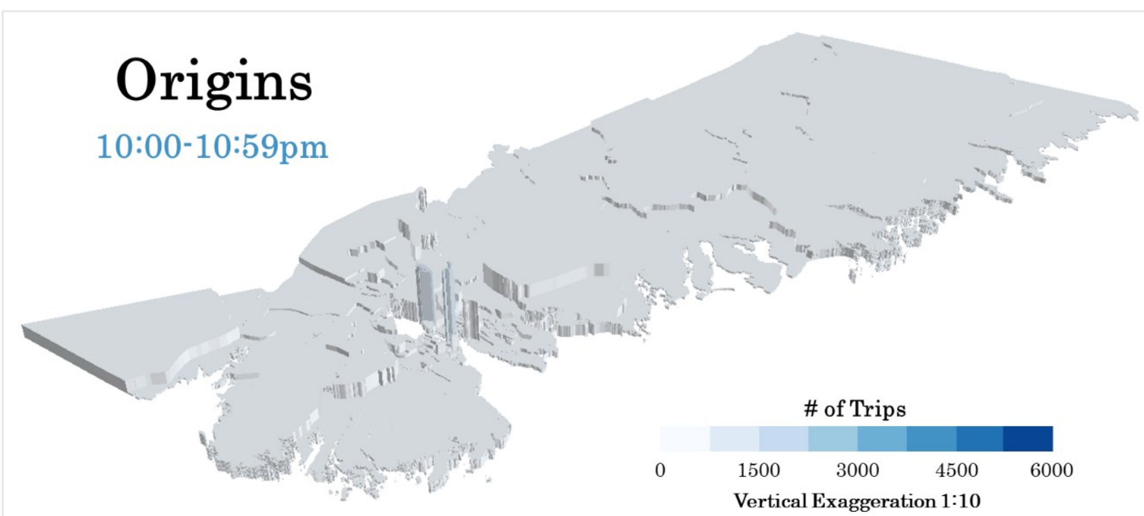

Destinations
7:00-7:59pm
# of Trips
0
1500
3000
4500
6000
Vertical Exaggeration 1:10

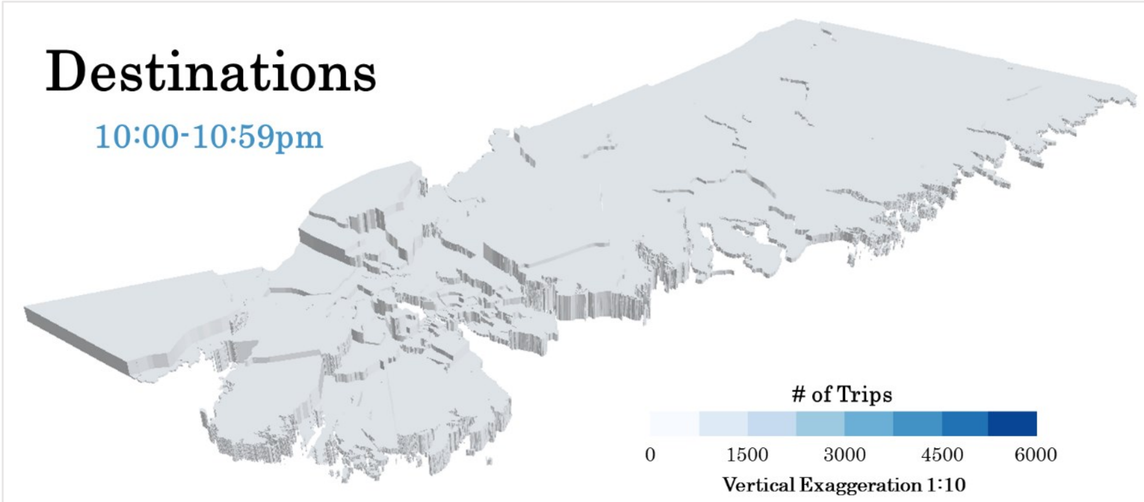

Origins
8:00-8:59pm
# of Trips
0
1500
3000
4500
6000
Vertical Exaggeration 1:10

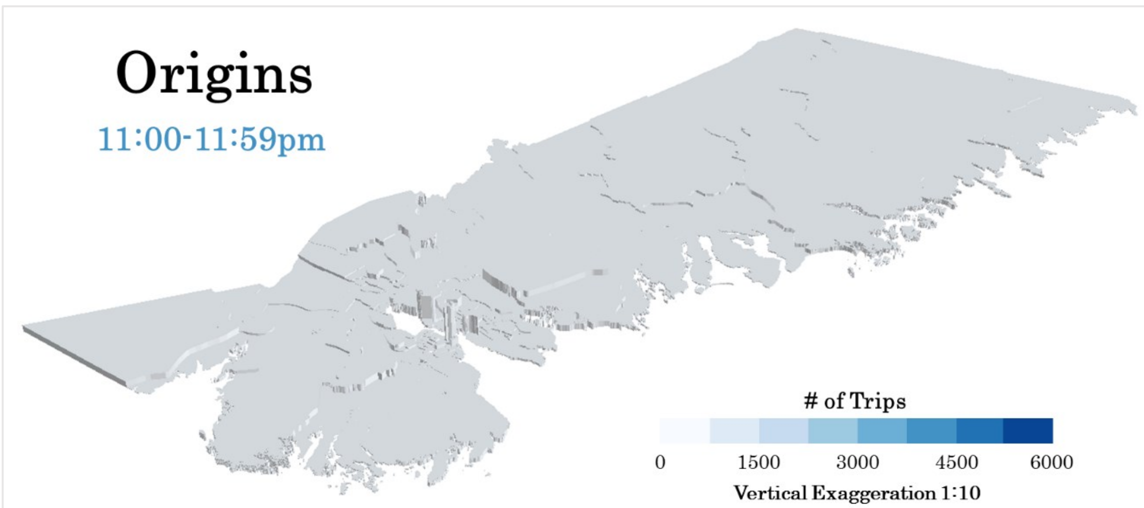

Destinations
8:00-8:59pm
# of Trips
0
1500
3000
4500
6000
Vertical Exaggeration 1:10

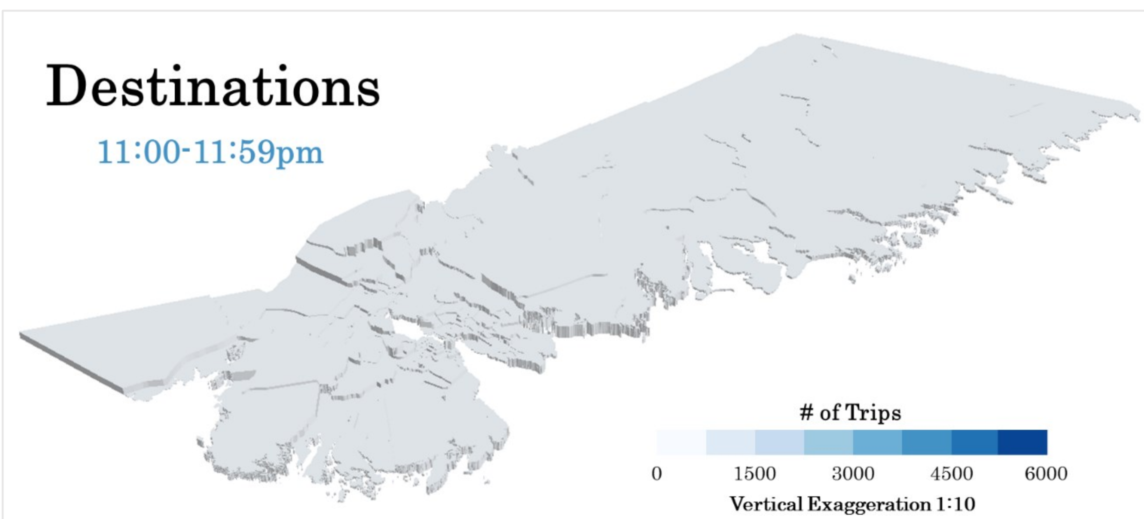

Origins
9:00-9:59pm
# of Trips
0
1500
3000
4500
6000
Vertical Exaggeration 1:10


Destinations
9:00-9:59pm
# of Trips
0
1500
3000
4500
6000
Vertical Exaggeration 1:10


Origins
10:00-10:59pm
# of Trips
0
1500
3000
4500
6000
Vertical Exaggeration 1:10


Destinations
10:00-10:59pm
# of Trips
0
1500
3000
4500
6000
Vertical Exaggeration 1:10


Origins
11:00-11:59pm
# of Trips
0
1500
3000
4500
6000
Vertical Exaggeration 1:10


Destinations
11:00-11:59pm
# of Trips
0
1500
3000
4500
6000
Vertical Exaggeration 1:10

Appendix F Sample Output of EMME

Figure F-1 Traffic Flow at Evening Peak Period in Transport Network Model

File Edit Options Tools

Traffic volume and times (on links)
By default, one-way links are shown in red.

Link filter: [road network] isAuto

	Heavy Truck	Medium Truck	Light Truck	Passenger Car	From	To	Length	Modes	Type	Lanes	VDF	Time	Speed	AutoVol	AddlVol	TotVol	VDT	VHT
	9.000000	**7.500000**	15.00000	59.00000	977	978	61.13	adefb	1	2.0	1	5.15e+09	7.12e-07	478953	0	478953	29277368	4.11e+13
	9.000000	**7.500000**	15.00000	59.00000	978	979	905.83	adefb	1	2.0	1	7.63e+10	7.12e-07	478953	0	478953	4.34e+08	6.09e+14
	9.000000	**7.500000**	15.00000	63.00000	979	980	218.60	adefb	1	2.0	1	1.84e+10	7.12e-07	478957	0	478957	1.05e+08	1.47e+14
	9.000000	**7.500000**	15.00000	63.00000	980	981	76.76	adefb	1	2.0	1	5.47e+09	7.12e-07	478957	0	478957	36767022	5.16e+13
	9.000000	**7.500000**	15.00000	63.00000	981	982	980.15	adefb	1	2.0	1	3.26e+10	7.12e-07	478957	0	478957	4.69e+08	6.59e+14
	9.000000	**7.500000**	15.00000	63.00000	982	984	185.38	adefb	1	2.0	1	1.56e+10	7.12e-07	478957	0	478957	88787687	1.25e+14
	9.000000	**7.500000**	15.00000	63.00000	984	983	291.07	adefb	1	2.0	1	2.45e+10	7.12e-07	478957	0	478957	1.39e+08	1.96e+14
	9.600000	**8.000000**	16.00000	1.000000	41	42	670.55	adefb	1	2.0	1	5.72e+11	7.04e-08	854256	0	854256	5.73e+08	8.14e+15
	9.600000	**8.000000**	16.00000	36.00000	41	47	499.89	adefb	1	2.0	1	5.01e+11	4.99e-08	930850	0	930850	4.65e+08	9.32e+15
	9.600000	**8.000000**	16.00000	36.00000	42	41	670.55	adefb	1	2.0	1	3.06e+11	4.99e-08	930850	0	930850	6.24e+08	1.25e+16
	9.600000	**8.000000**	16.00000	1.000000	47	41	499.89	adefb	1	2.0	1	4.26e+11	7.04e-08	854256	0	854256	4.27e+08	6.07e+15
	9.600000	**8.000000**	16.00000	36.00000	47	976	501.16	adefb	1	2.0	1	5.02e+11	4.99e-08	930850	0	930850	4.67e+08	9.34e+15
	9.600000	**8.000000**	16.00000	22.00000	321	335	470.97	adefb	2	2.0	2	3.77e+11	7.49e-08	559484	0	559484	2.64e+08	3.52e+15
	9.600000	**8.000000**	16.00000	22.00000	335	336	31.18	adefb	2	2.0	2	2.5e+10	7.49e-08	559484	0	559484	17443137	2.33e+14
	9.600000	**8.000000**	16.00000	22.00000	336	337	34.73	adefb	2	2.0	2	2.78e+10	7.49e-08	559484	0	559484	19428856	2.59e+14
	9.600000	**8.000000**	16.00000	22.00000	337	1203	315.35	adefb	2	2.0	2	2.53e+11	7.49e-08	559484	0	559484	1.76e+08	2.36e+15
	9.600000	**8.000000**	16.00000	22.00000	360	365	141.76	adefb	2	2.0	2	1.14e+11	7.49e-08	559484	0	559484	79314095	1.06e+15
	9.600000	**8.000000**	16.00000	22.00000	365	370	51.67	adefb	2	2.0	2	4.14e+10	7.49e-08	559484	0	559484	28908582	3.86e+14
	9.600000	**8.000000**	16.00000	22.00000	370	1202	84.95	adefb	2	2.0	2	3.6e+10	1.41e-07	477317	0	477317	40547005	2.87e+14
	9.600000	**8.000000**	16.00000	22.00000	378	371	135.69	adefb	2	2.0	2	5.76e+10	1.41e-07	477317	0	477317	64768061	4.58e+14
	9.600000	**8.000000**	16.00000	26.00000	396	319	630.45	adefb	2	2.0	2	7.29e+10	5.19e-07	344833	0	344833	2.17e+08	4.19e+14
	9.600000	**8.000000**	16.00000	4.000000	740	743	93.61	adefb	2	2.0	2	4.42e+10	1.27e-07	490289	0	490289	45897226	3.61e+14
	9.600000	**8.000000**	16.00000	0.000000	743	750	98.39	adefb	2	2.0	2	4e+10	1.48e-07	472144	0	472144	46454123	3.15e+14
	9.600000	**8.000000**	16.00000	4.000000	743	771	37.39	adefb	2	2.0	2	1.77e+10	1.27e-07	490289	0	490289	18331218	1.44e+14
	9.600000	**8.000000**	16.00000	4.000000	745	755	97.35	adefb	2	2.0	2	4.6e+10	1.27e-07	490289	0	490289	47729582	3.76e+14
	9.600000	**8.000000**	16.00000	0.000000	745	771	37.69	adefb	2	2.0	2	1.53e+10	1.48e-07	472144	0	472144	17796955	1.2e+14
	9.600000	**8.000000**	16.00000	0.000000	755	745	97.35	adefb	2	2.0	2	3.95e+10	1.48e-07	472144	0	472144	45963186	3.11e+14
	9.600000	**8.000000**	16.00000	4.000000	755	766	87.43	adefb	2	2.0	2	4.13e+10	1.27e-07	490289	0	490289	42866649	3.37e+14
	9.600000	**8.000000**	16.00000	0.000000	766	755	87.43	adefb	2	2.0	2	3.55e+10	1.48e-07	472144	0	472144	41280223	2.79e+14
	9.600000	**8.000000**	16.00000	4.000000	766	770	98.01	adefb	2	2.0	2	4.63e+10	1.27e-07	490289	0	490289	48053956	3.78e+14
Min:							12.60		1	2.0	1	10.80	5.82e-10	0	0	0		
Max:							14712		5	2.0	5	2.15e+13	100.00	1907476	0	1907476		
Sum:							1.95e+06					3.47e+14					1.89e+11	7.56e+18
Avg:							373.95					5.65e+10	31.87	120458	0	120458		

Figure F-2 Link-based Classified Traffic Volume and Other Attributes

Appendix G Average Speed Profile of all Vehicles for the Model Year of 2016

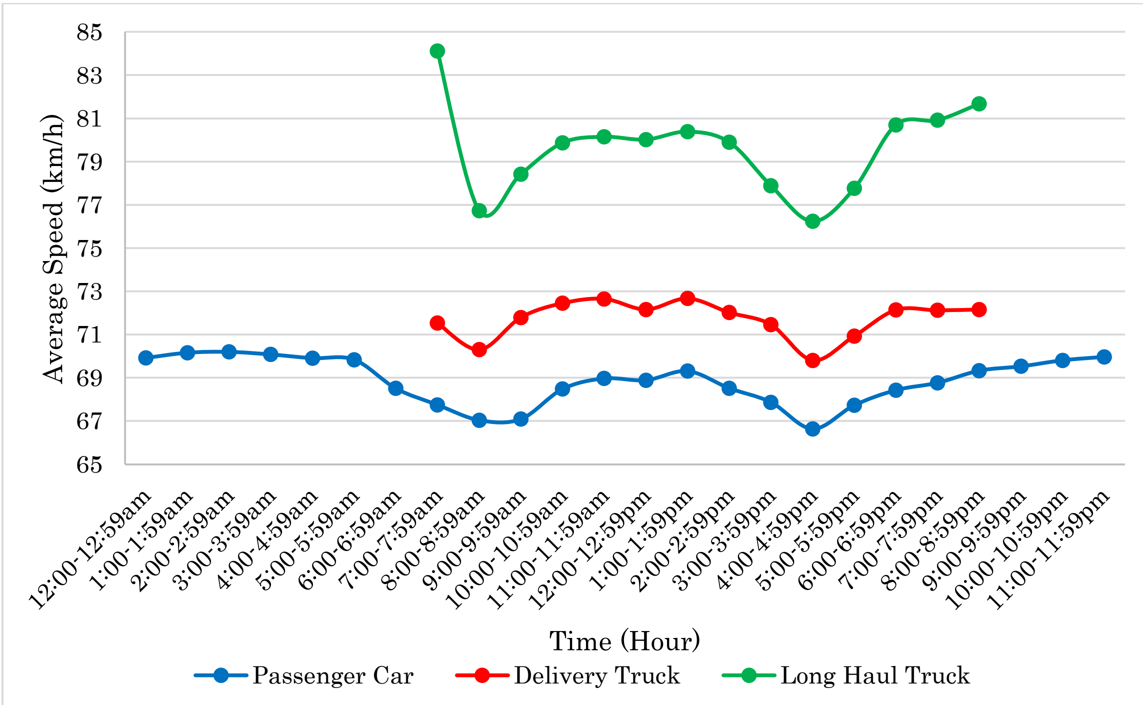


Figure G-1 Average Speed Profile of all Vehicles

Appendix H Hourly Profile for Total Emission for the Model Year of 2011

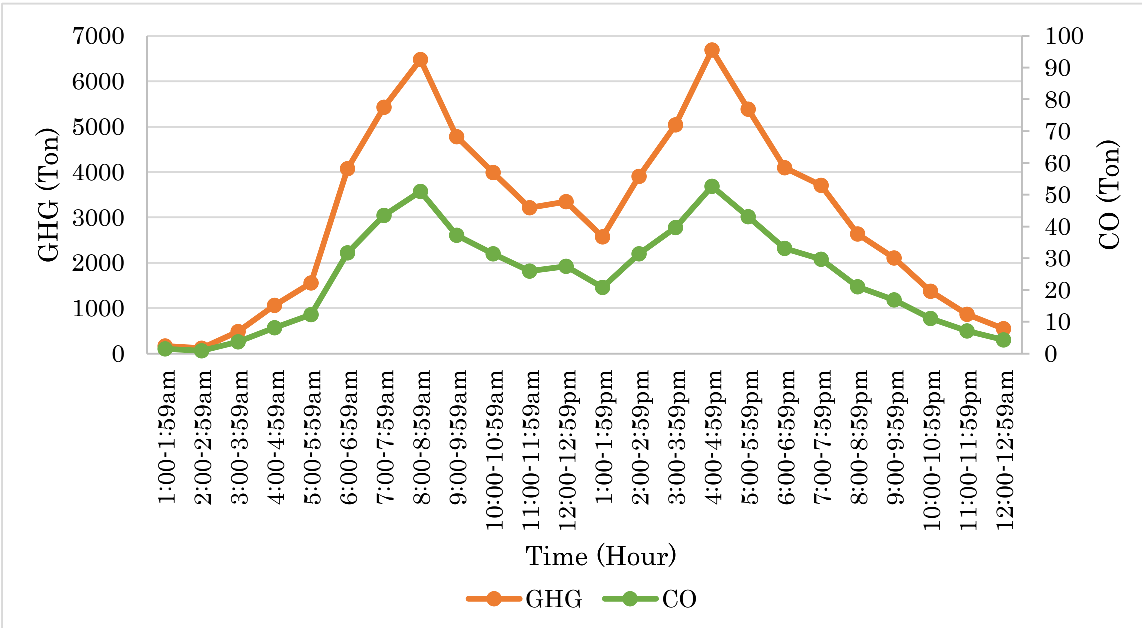


Figure H-1 Hourly Profile for Total Emission of GHG and CO

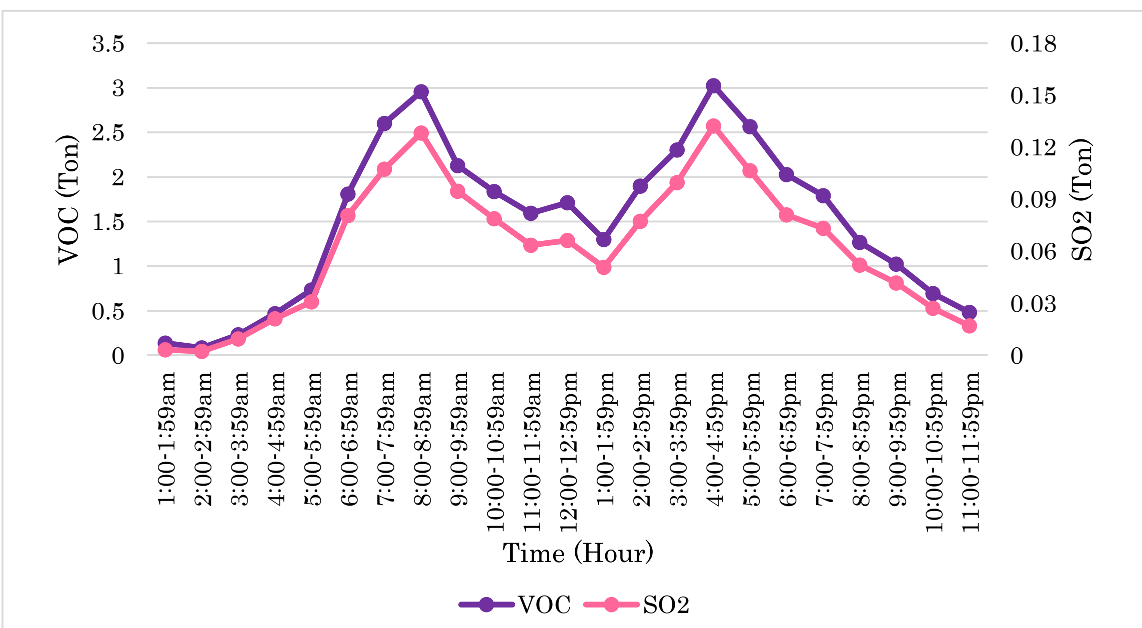


Figure H-2 Hourly Profile for Total Emission of VOC and SO_2

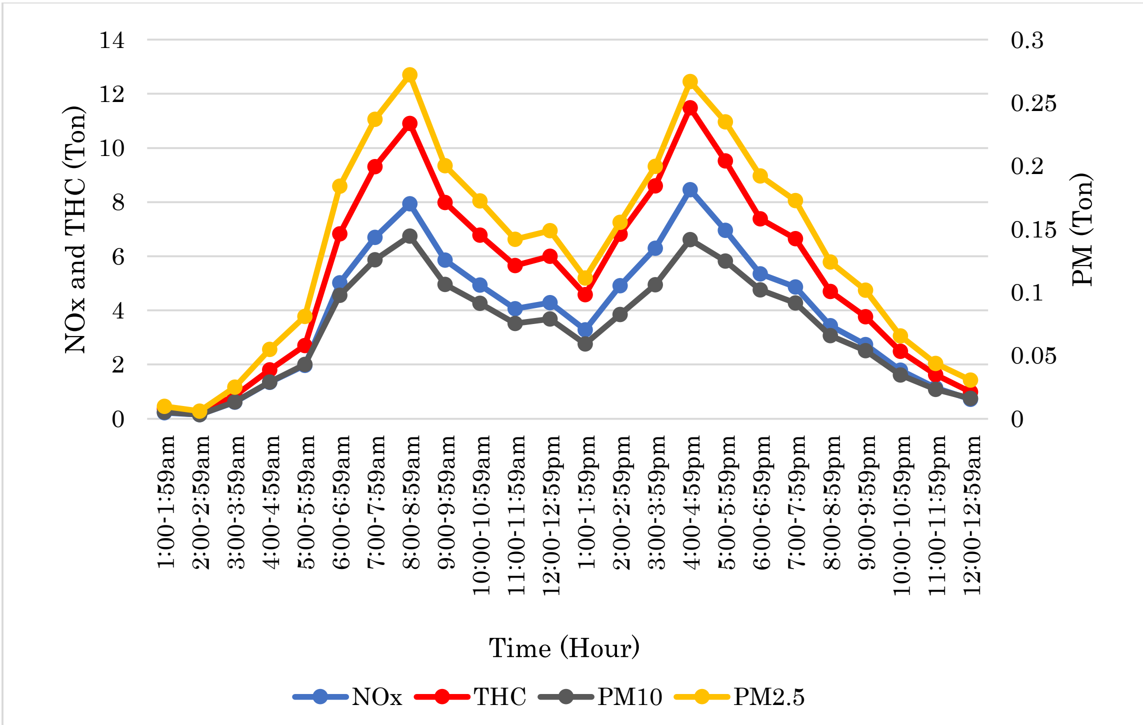
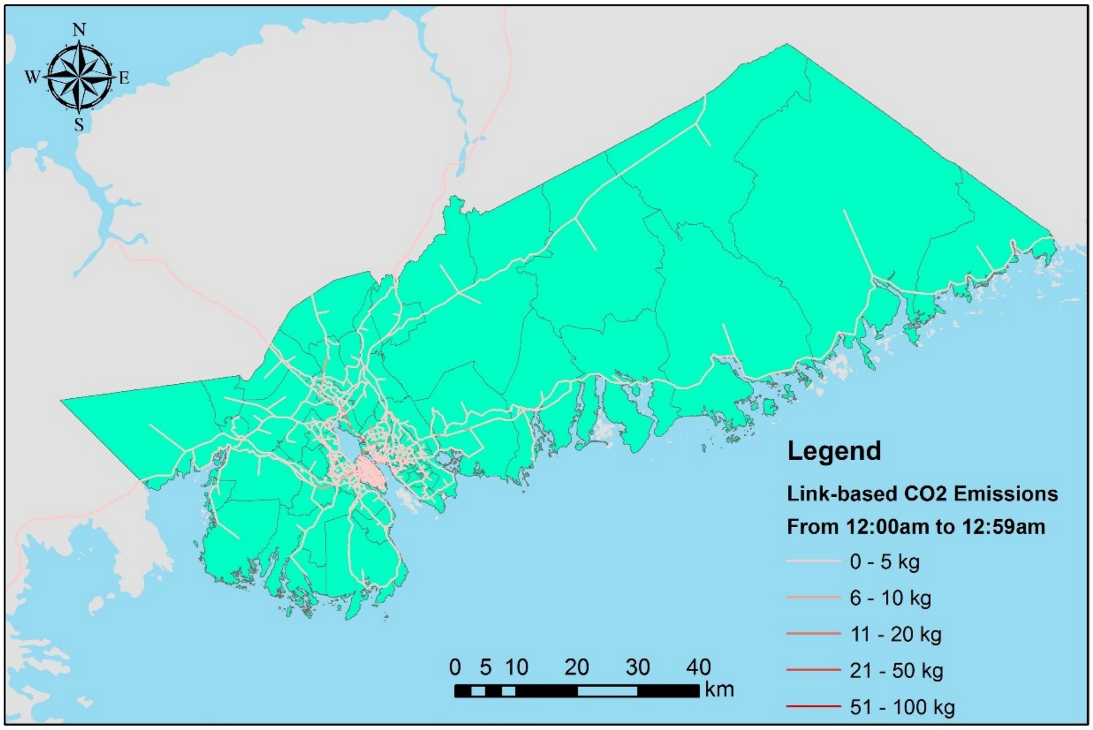
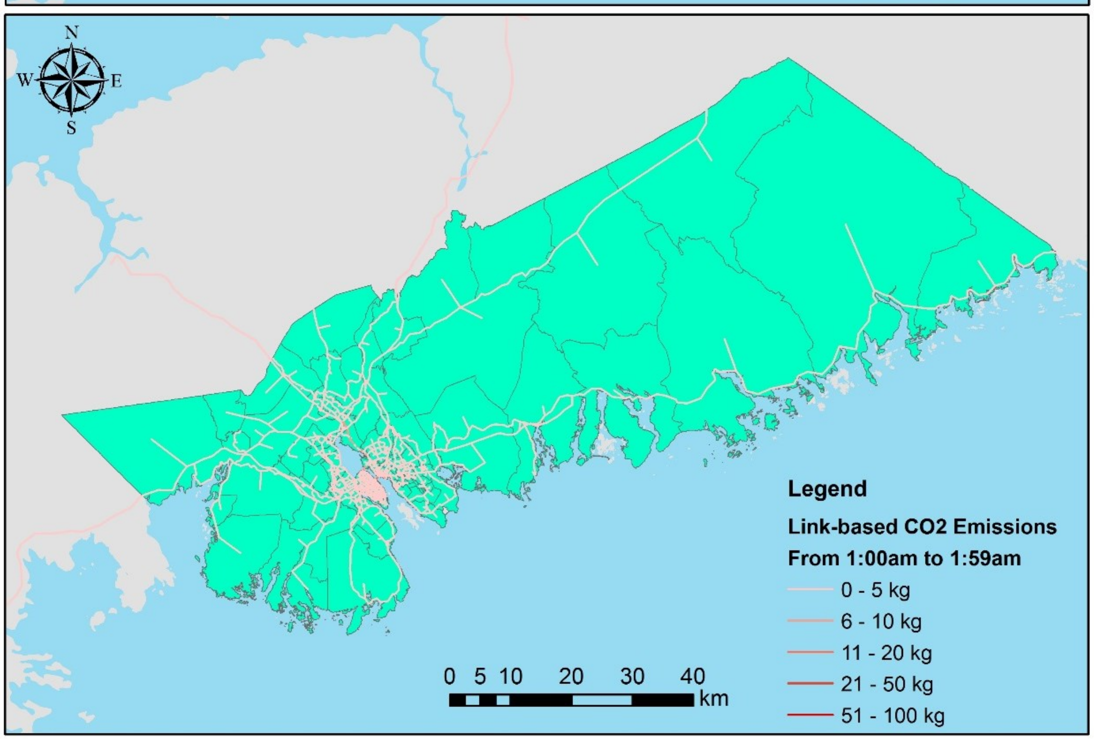
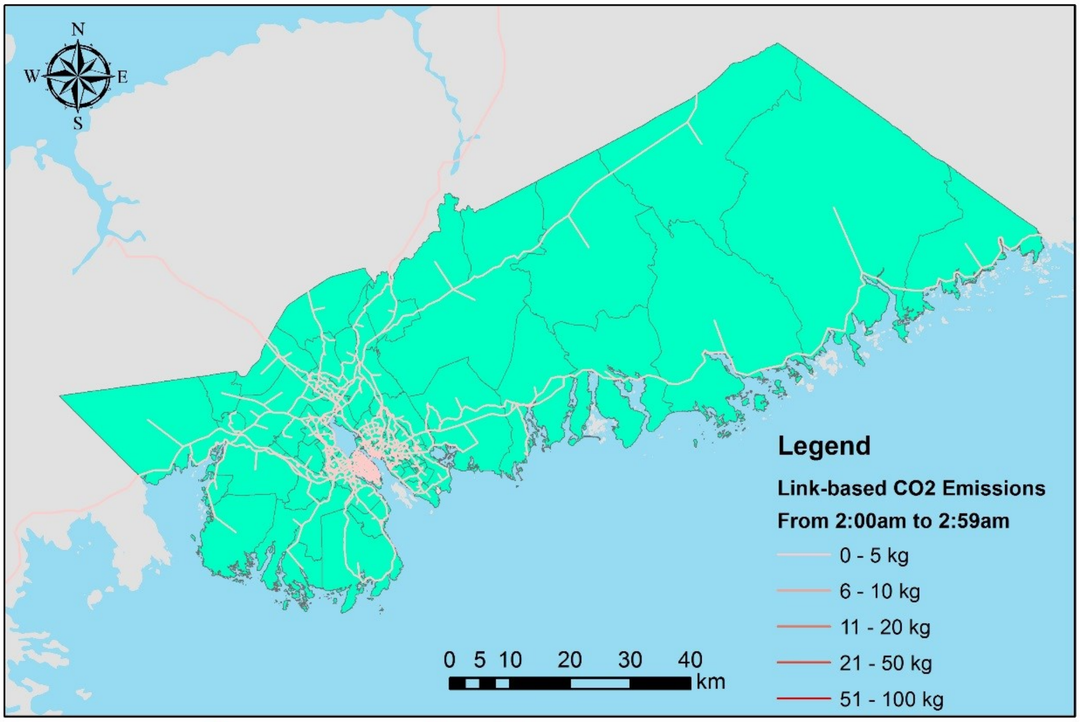


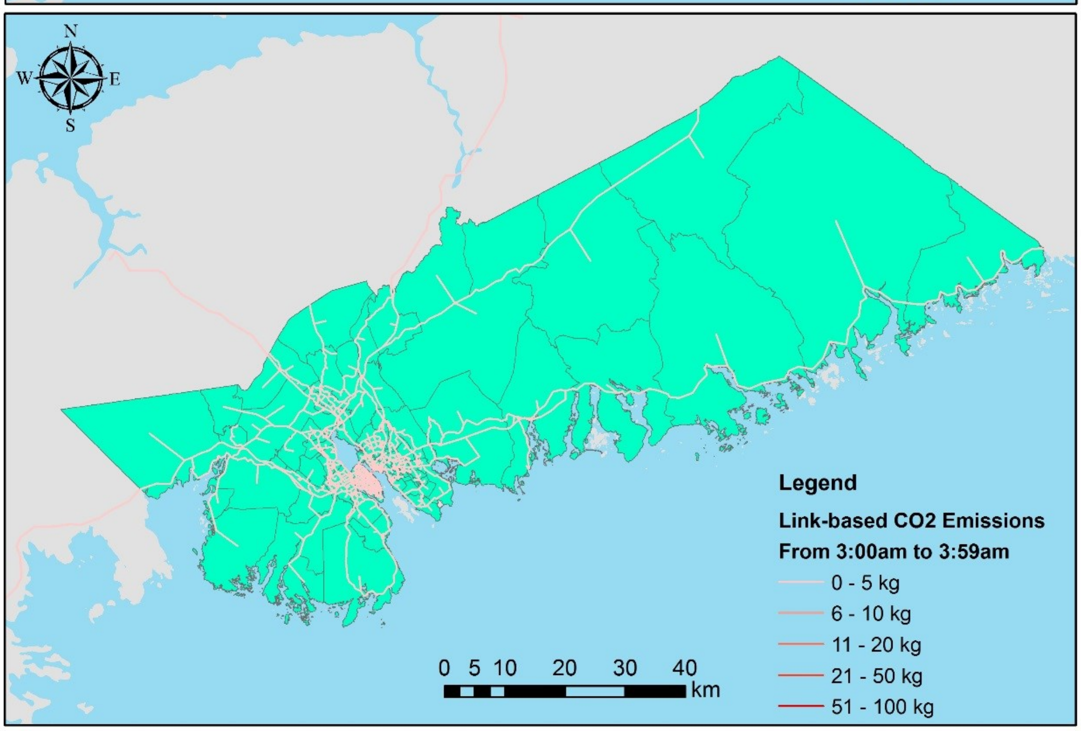
Figure H-3 Hourly Profile for Total Emission of NOx, THC and PM

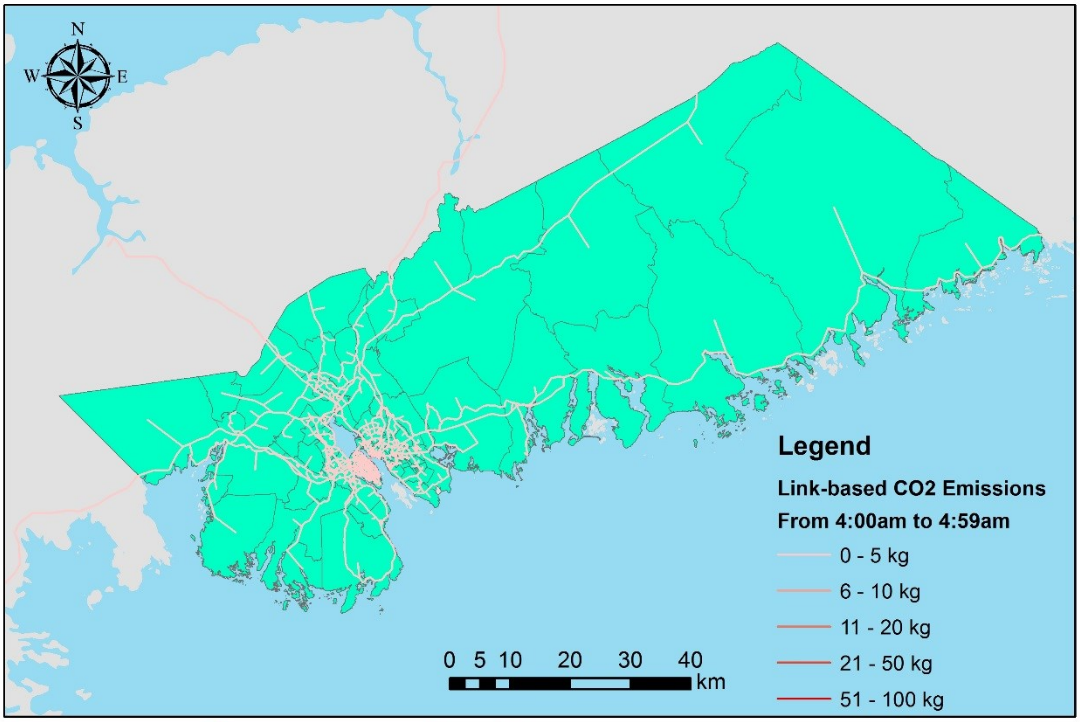
Appendix I 24-hour Link-based GHG Emission for the Model Year of 2011

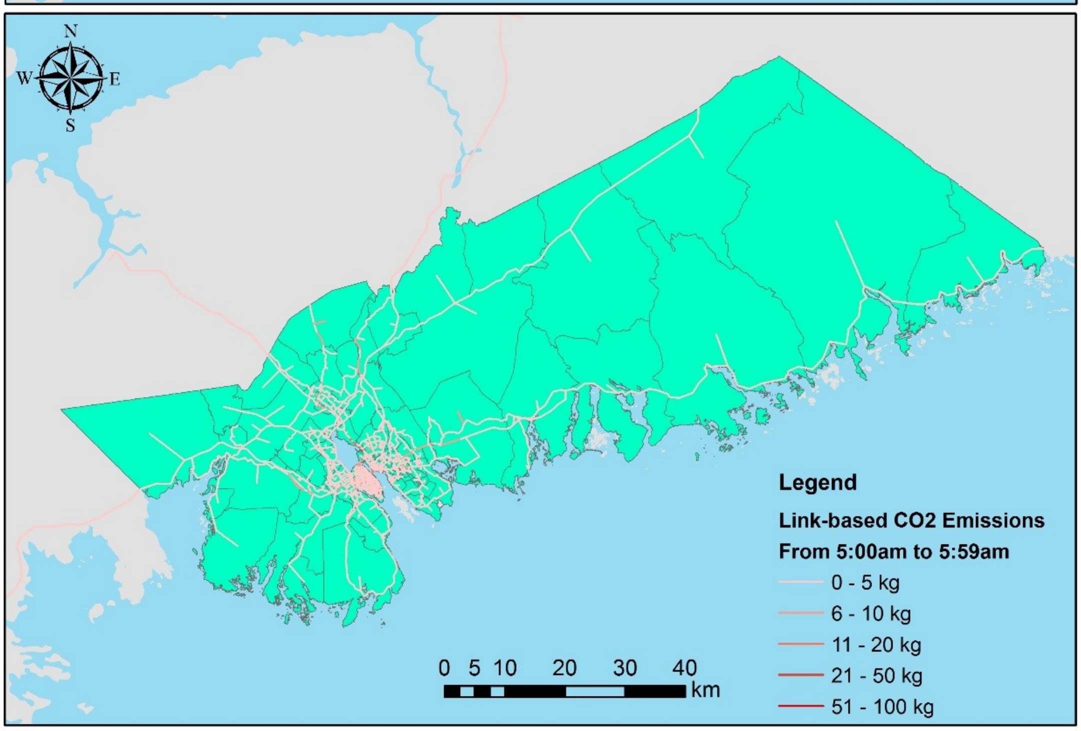


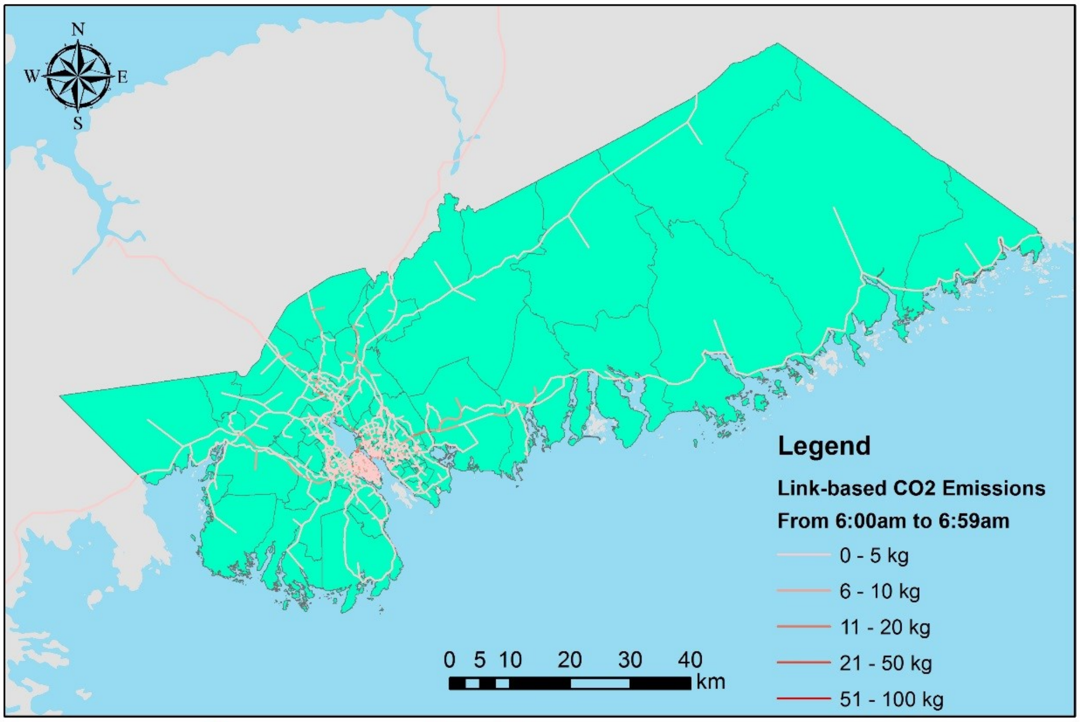


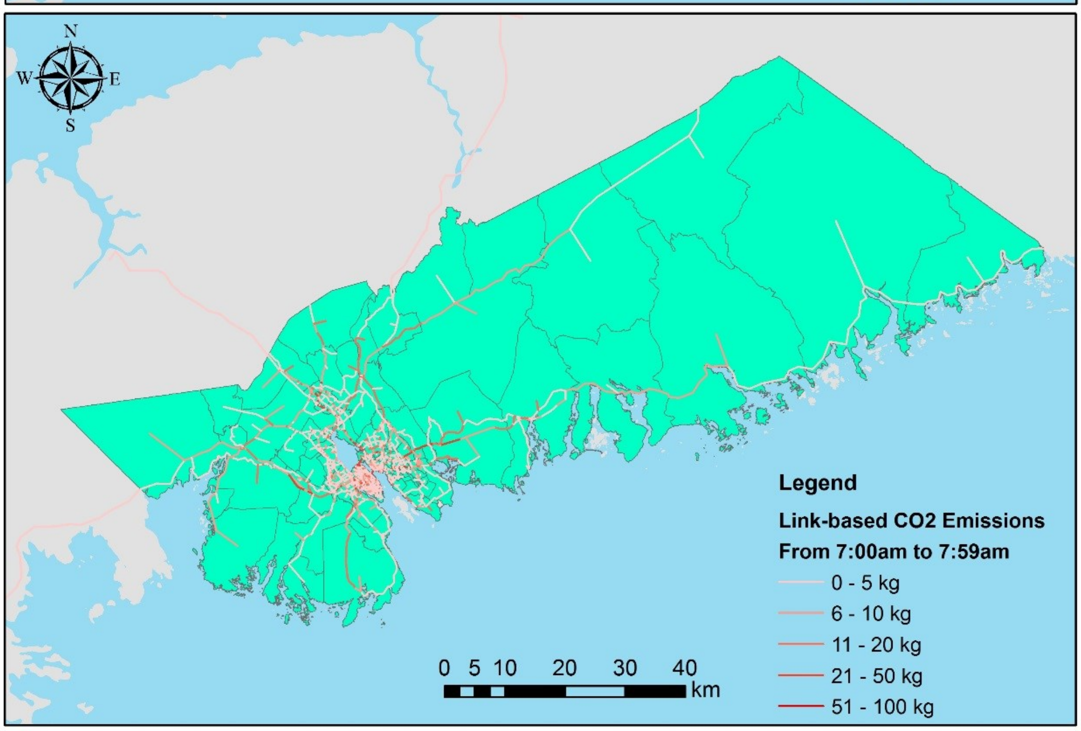

N
W
E
S
Legend
Link-based CO2 Emissions
From 2:00am to 2:59am
0 - 5 kg
6 - 10 kg
11 - 20 kg
21 - 50 kg
51 - 100 kg
0 5 10 20 30 40
km

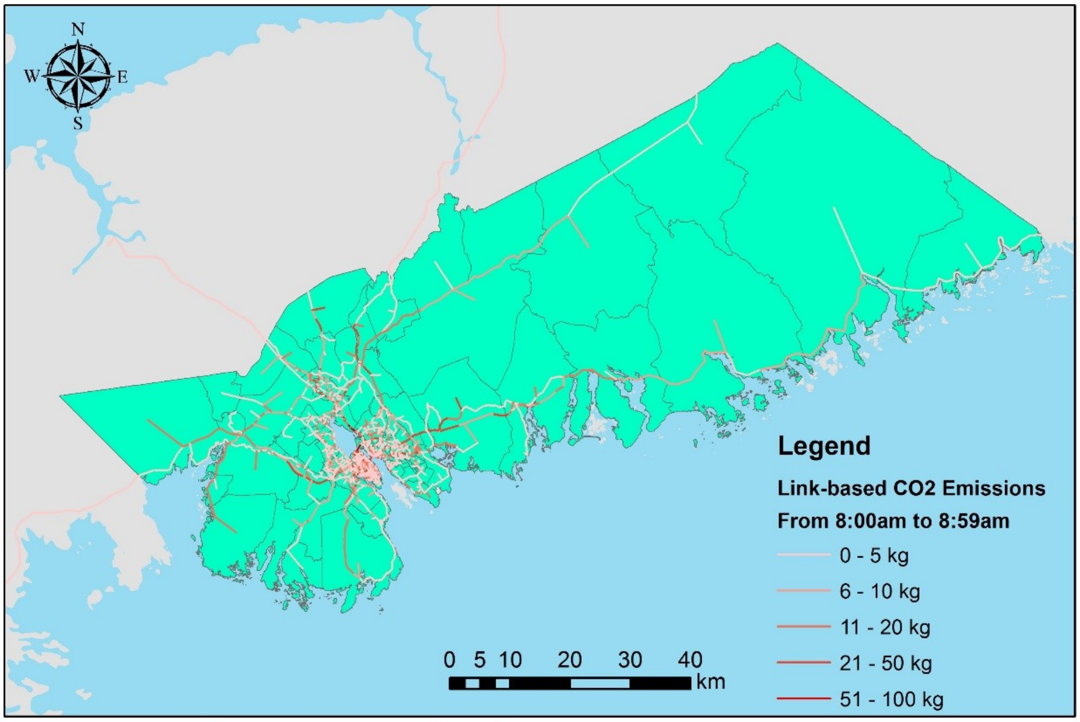

N
W
E
S
Legend
Link-based CO2 Emissions
From 3:00am to 3:59am
0 - 5 kg
6 - 10 kg
11 - 20 kg
21 - 50 kg
51 - 100 kg
0 5 10 20 30 40
km

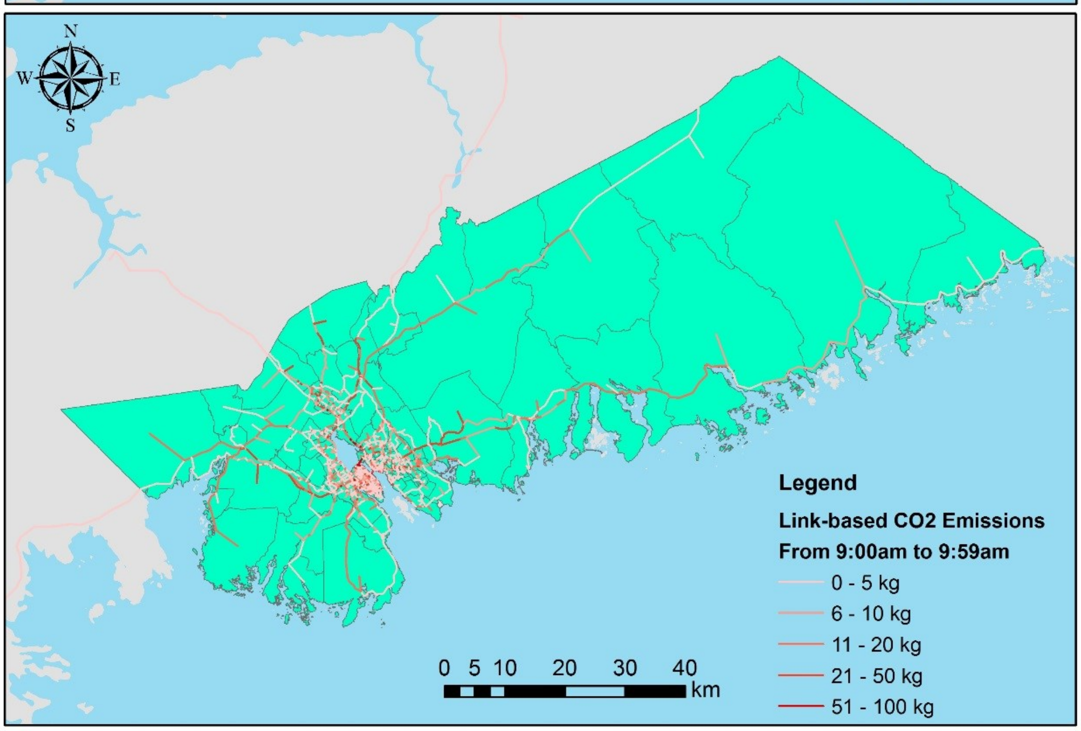

N
W
E
S
Legend
Link-based CO2 Emissions
From 4:00am to 4:59am
0 - 5 kg
6 - 10 kg
11 - 20 kg
21 - 50 kg
51 - 100 kg
0 5 10 20 30 40
km

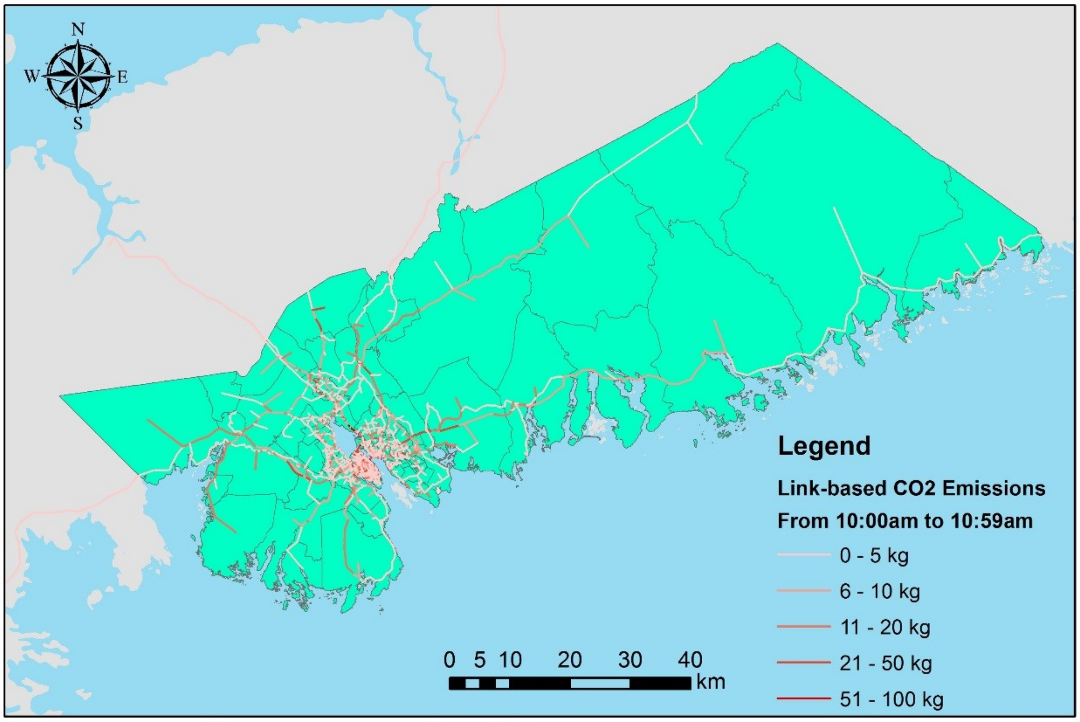

N
W
E
S
Legend
Link-based CO2 Emissions
From 5:00am to 5:59am
0 - 5 kg
6 - 10 kg
11 - 20 kg
21 - 50 kg
51 - 100 kg
0 5 10 20 30 40
km

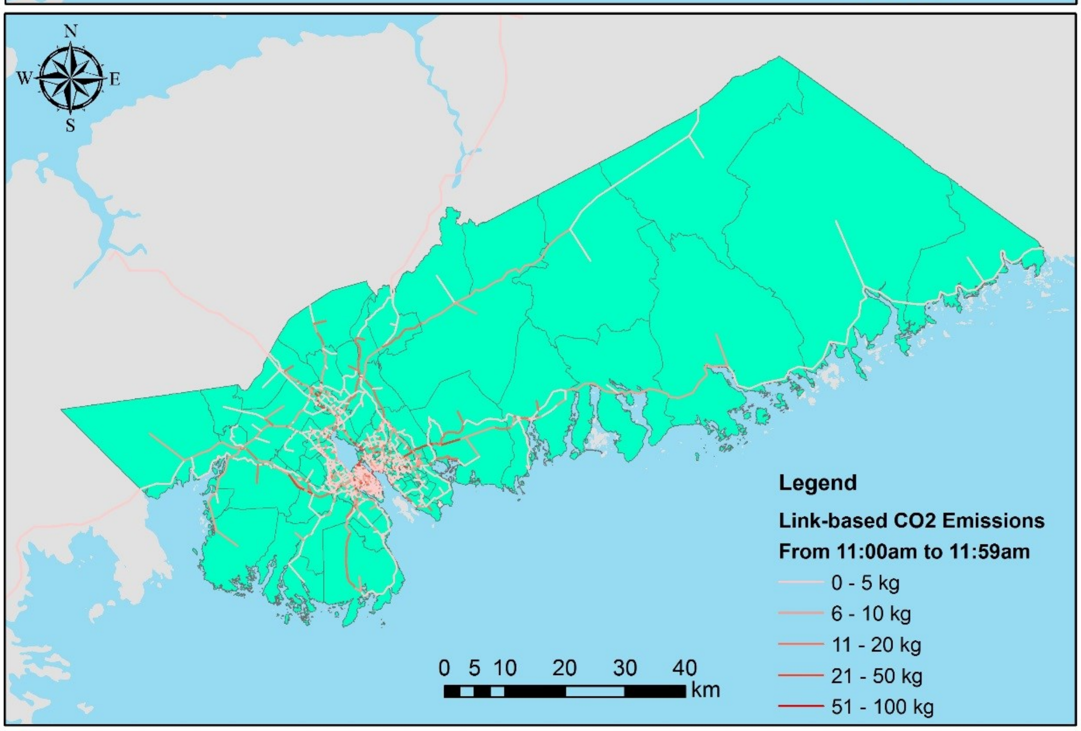

N
W
E
S
Legend
Link-based CO2 Emissions
From 6:00am to 6:59am
0 - 5 kg
6 - 10 kg
11 - 20 kg
21 - 50 kg
51 - 100 kg
0 5 10 20 30 40
km

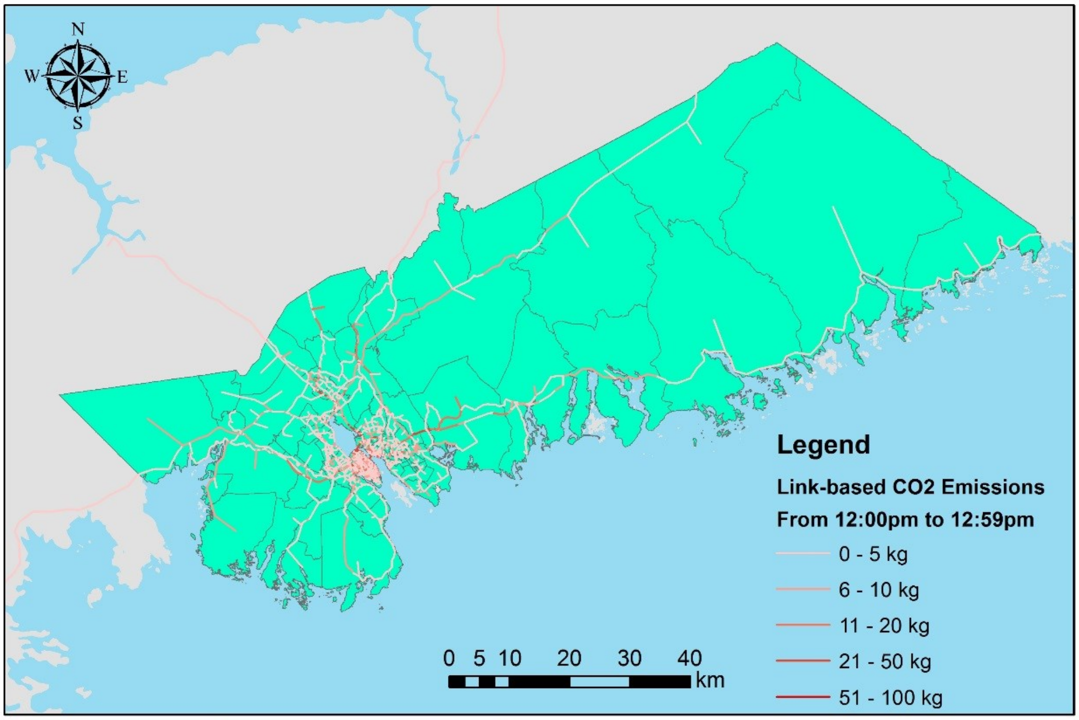

N
W
E
S
Legend
Link-based CO2 Emissions
From 7:00am to 7:59am
0 - 5 kg
6 - 10 kg
11 - 20 kg
21 - 50 kg
51 - 100 kg
0 5 10 20 30 40
km

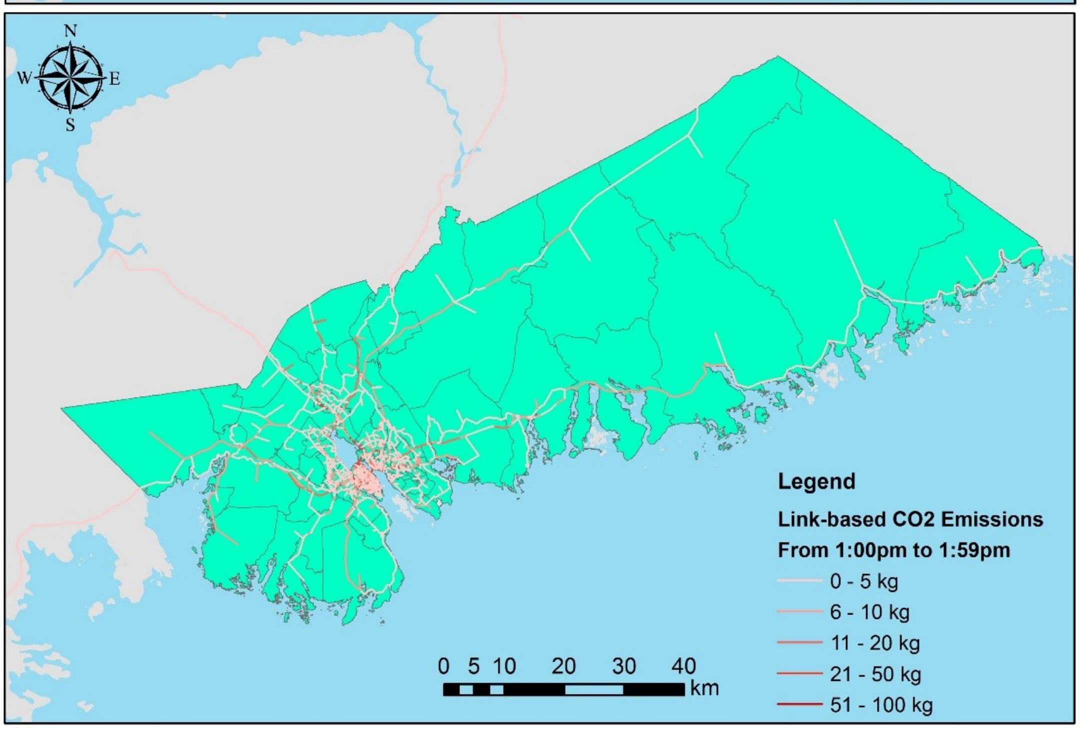

N
W
E
S
Legend
Link-based CO2 Emissions
From 8:00am to 8:59am
0 - 5 kg
6 - 10 kg
11 - 20 kg
21 - 50 kg
51 - 100 kg
0 5 10 20 30 40
km

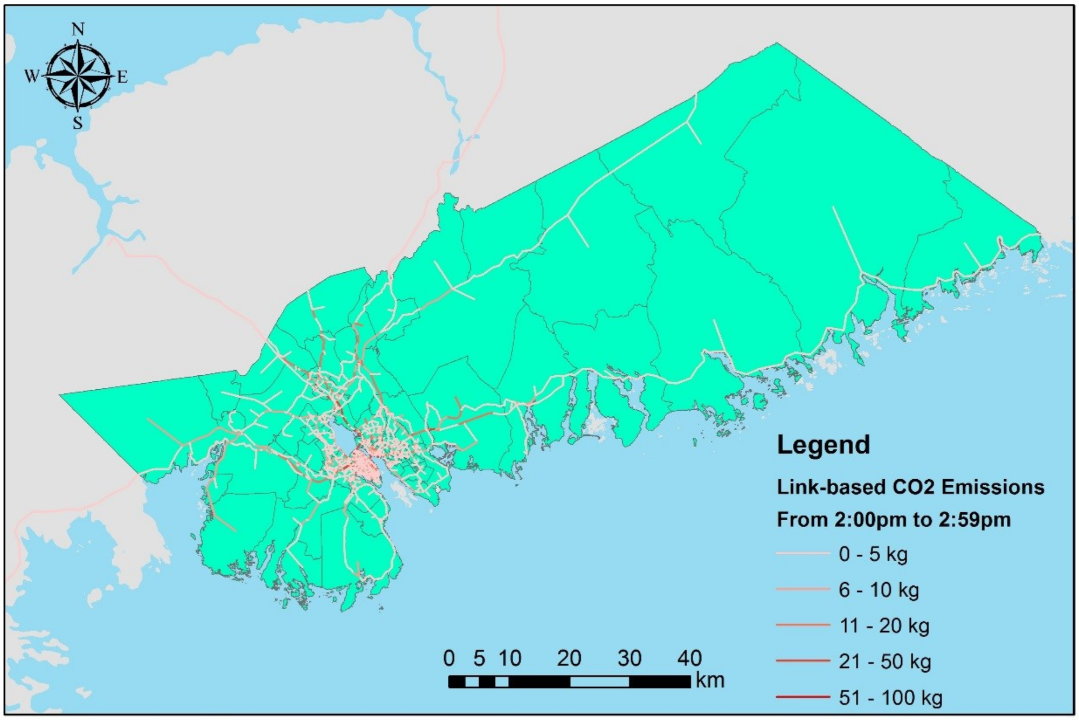

N
W
E
S
Legend
Link-based CO2 Emissions
From 9:00am to 9:59am
0 - 5 kg
6 - 10 kg
11 - 20 kg
21 - 50 kg
51 - 100 kg
0 5 10 20 30 40
km

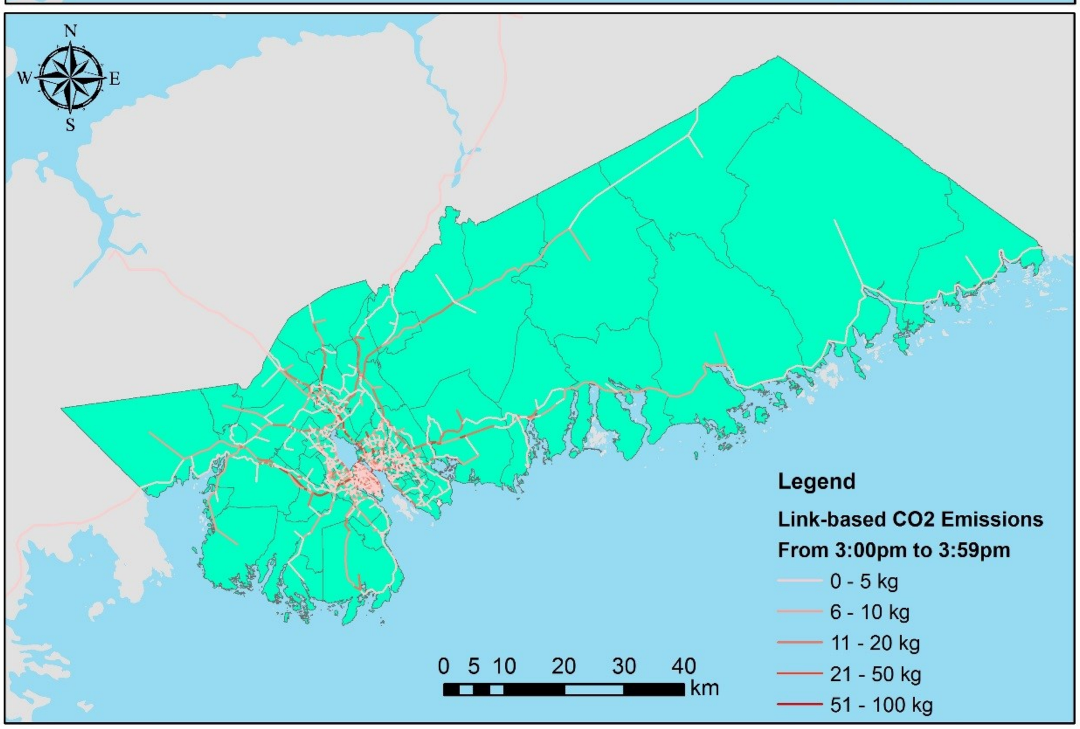

N
W
E
S
Legend
Link-based CO2 Emissions
From 10:00am to 10:59am
0 - 5 kg
6 - 10 kg
11 - 20 kg
21 - 50 kg
51 - 100 kg
0 5 10 20 30 40
km

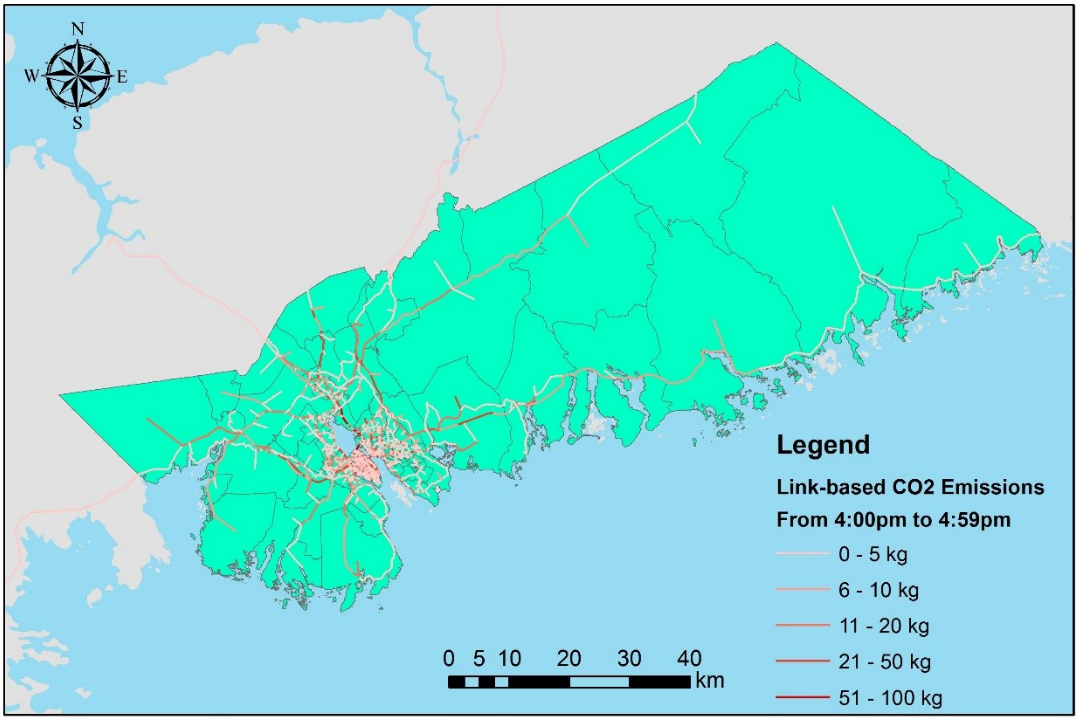

N
W
E
S
Legend
Link-based CO2 Emissions
From 11:00am to 11:59am
0 - 5 kg
6 - 10 kg
11 - 20 kg
21 - 50 kg
51 - 100 kg
0 5 10 20 30 40
km

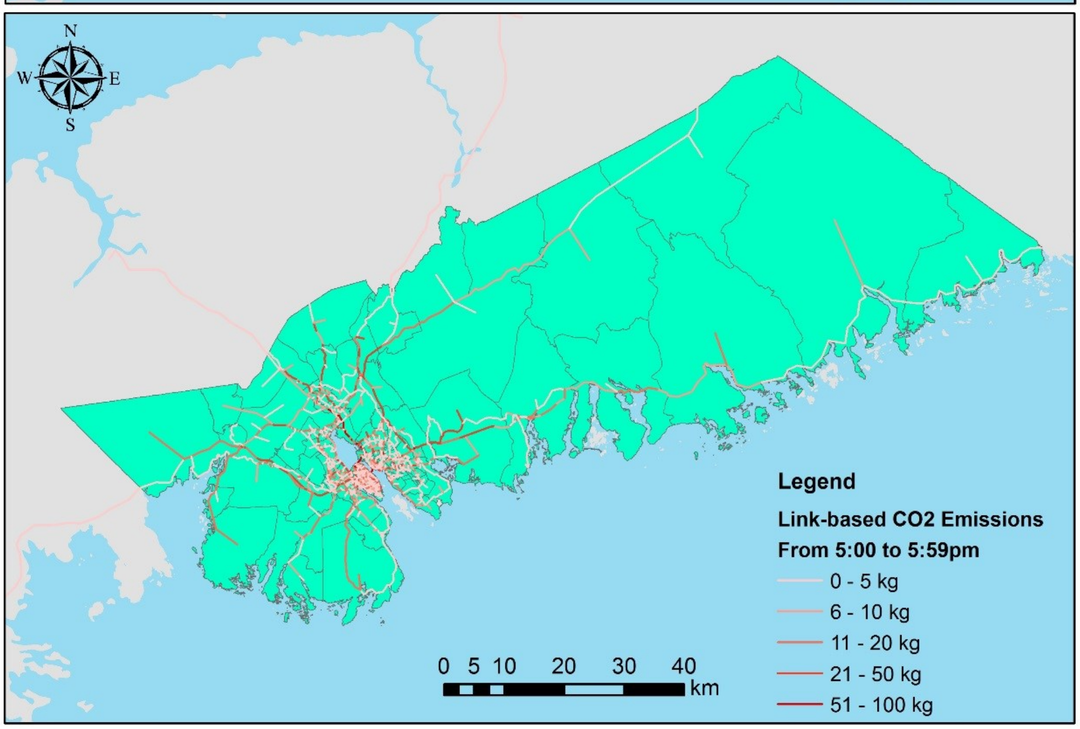

N
W
E
S
Legend
Link-based CO2 Emissions
From 12:00pm to 12:59pm
0 - 5 kg
6 - 10 kg
11 - 20 kg
21 - 50 kg
51 - 100 kg
0 5 10 20 30 40
km

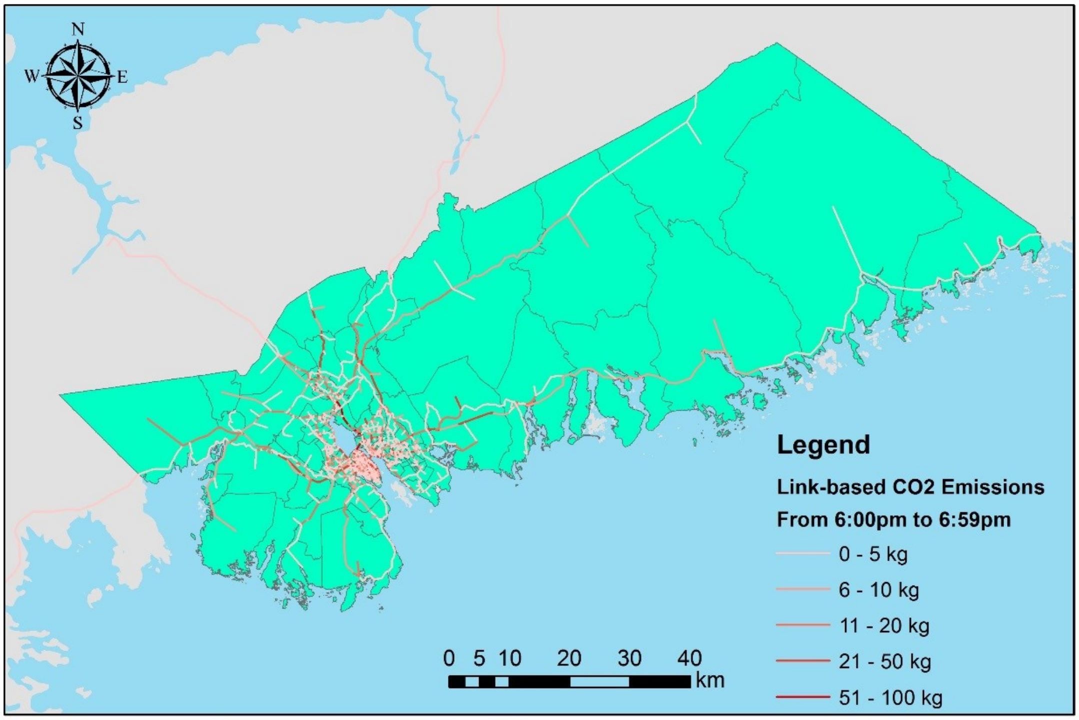

N
W
E
S
Legend
Link-based CO2 Emissions
From 1:00pm to 1:59pm
0 - 5 kg
6 - 10 kg
11 - 20 kg
21 - 50 kg
51 - 100 kg
0 5 10 20 30 40
km

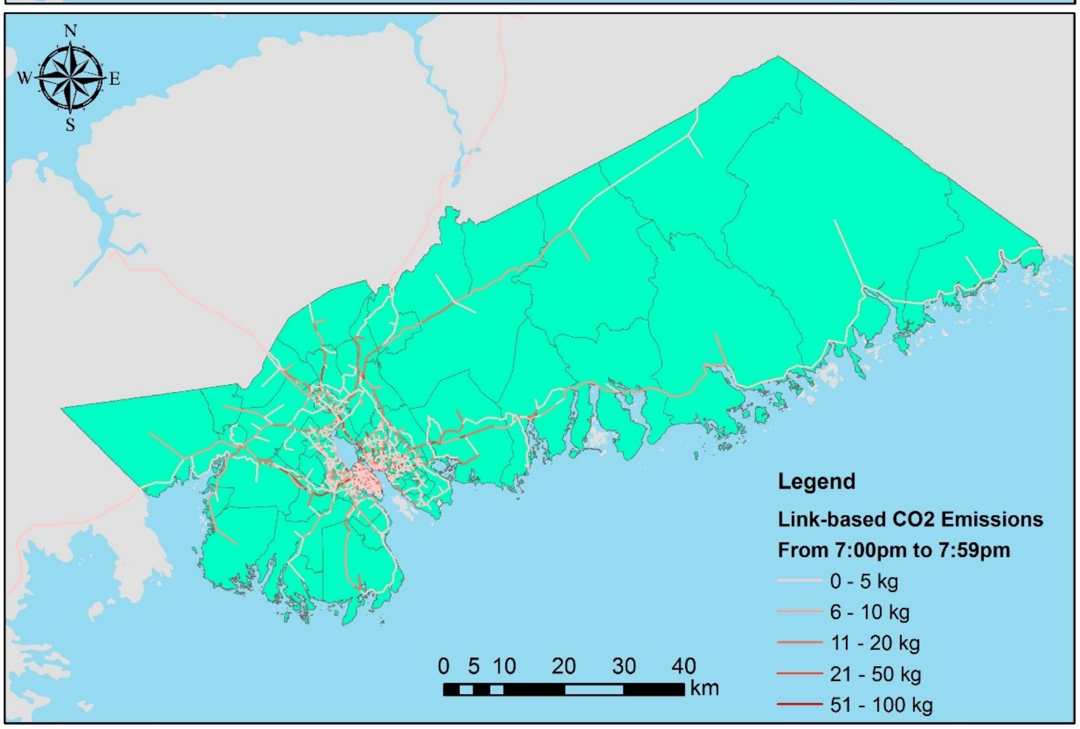

N
W
E
S
Legend
Link-based CO2 Emissions
From 2:00pm to 2:59pm
0 - 5 kg
6 - 10 kg
11 - 20 kg
21 - 50 kg
51 - 100 kg
0 5 10 20 30 40
km

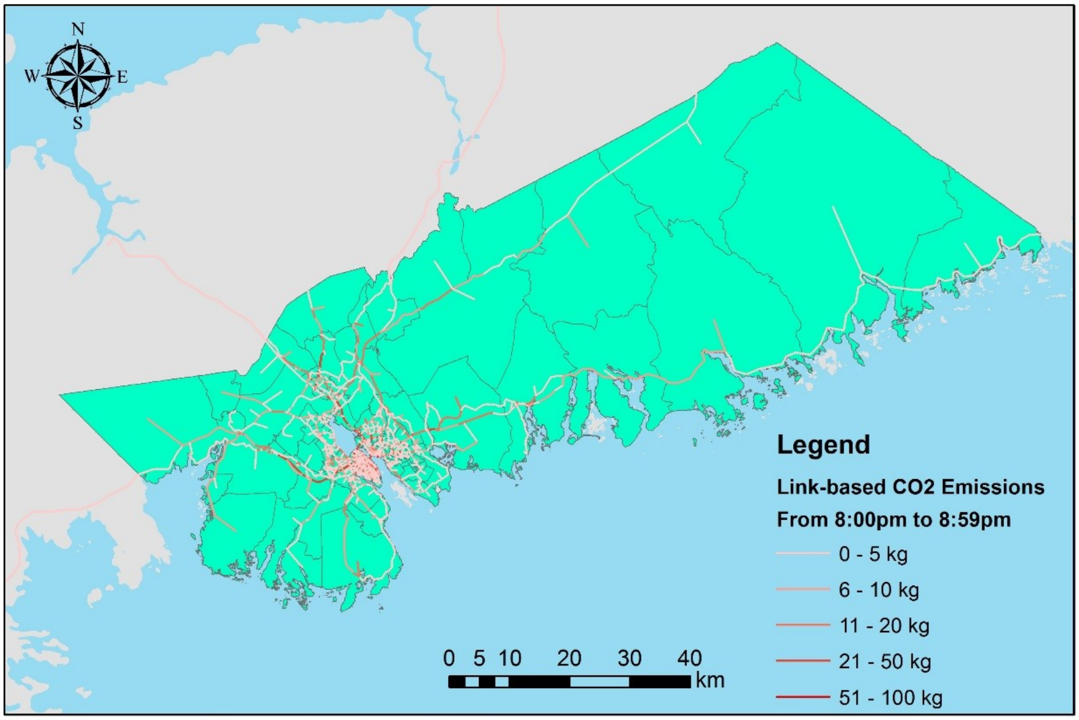

N
W
E
S
Legend
Link-based CO2 Emissions
From 3:00pm to 3:59pm
0 - 5 kg
6 - 10 kg
11 - 20 kg
21 - 50 kg
51 - 100 kg
0 5 10 20 30 40
km

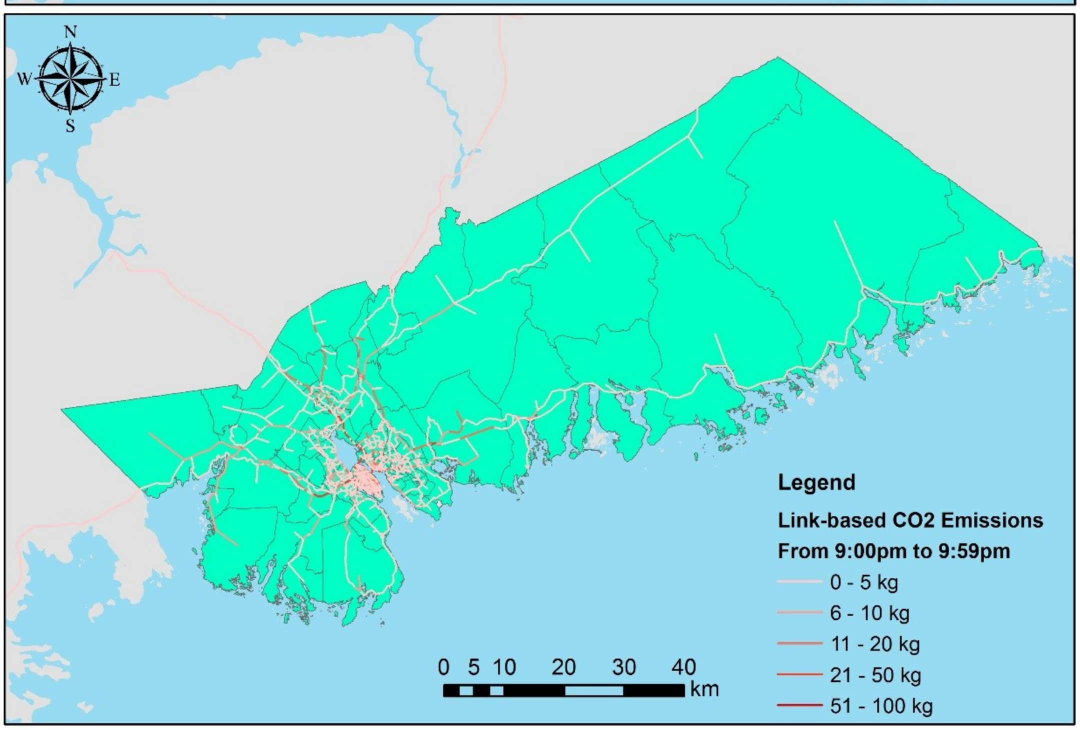

N
W
E
S
Legend
Link-based CO2 Emissions
From 4:00pm to 4:59pm
0 - 5 kg
6 - 10 kg
11 - 20 kg
21 - 50 kg
51 - 100 kg
0 5 10 20 30 40
km

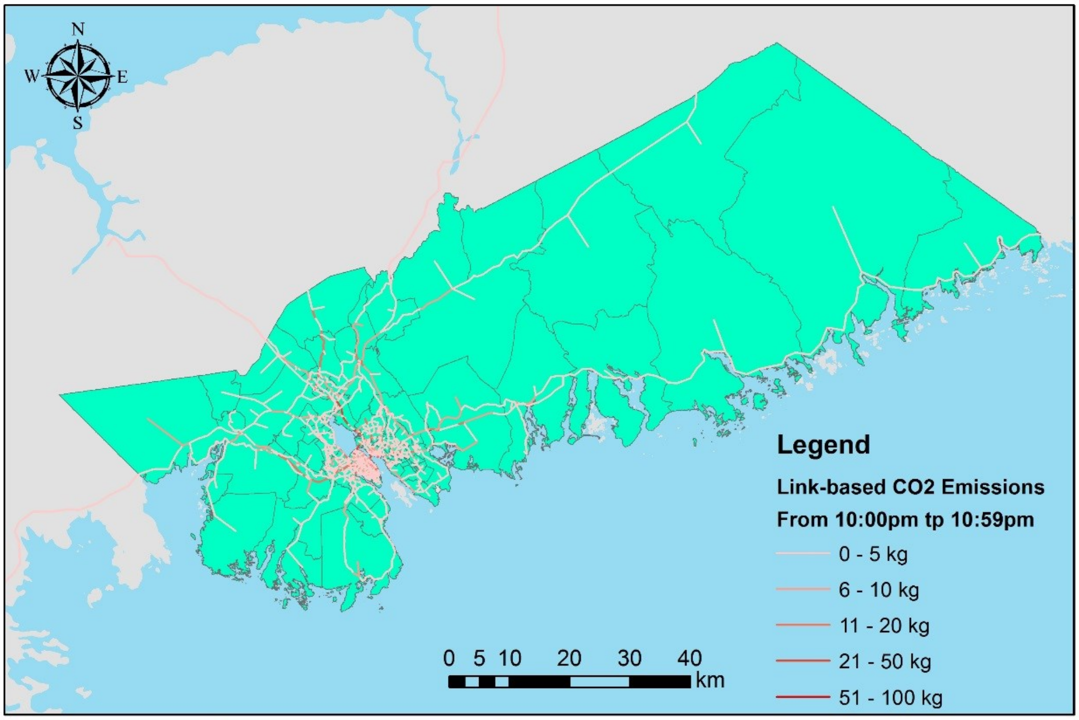

N
W
E
S
Legend
Link-based CO2 Emissions
From 5:00 to 5:59pm
0 - 5 kg
6 - 10 kg
11 - 20 kg
21 - 50 kg
51 - 100 kg
0 5 10 20 30 40
km

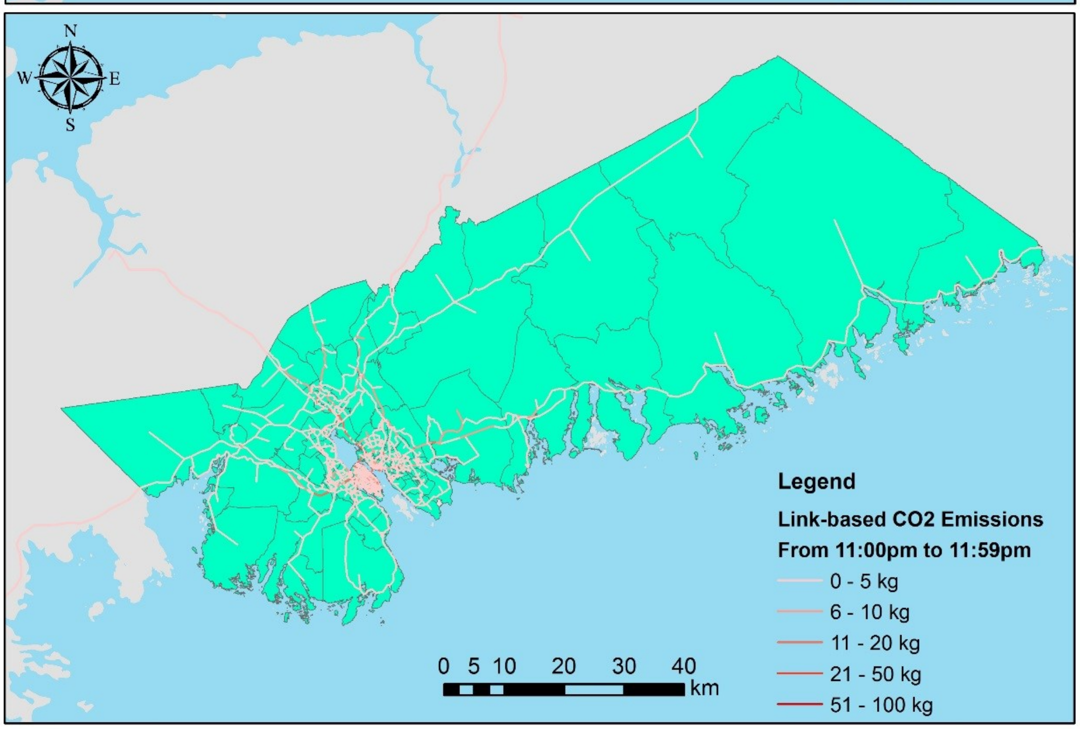

N
W
E
S
Legend
Link-based CO2 Emissions
From 6:00pm to 6:59pm
0 - 5 kg
6 - 10 kg
11 - 20 kg
21 - 50 kg
51 - 100 kg
0 5 10 20 30 40
km


N
W
E
S
Legend
Link-based CO2 Emissions
From 7:00pm to 7:59pm
0 - 5 kg
6 - 10 kg
11 - 20 kg
21 - 50 kg
51 - 100 kg
0 5 10 20 30 40
km

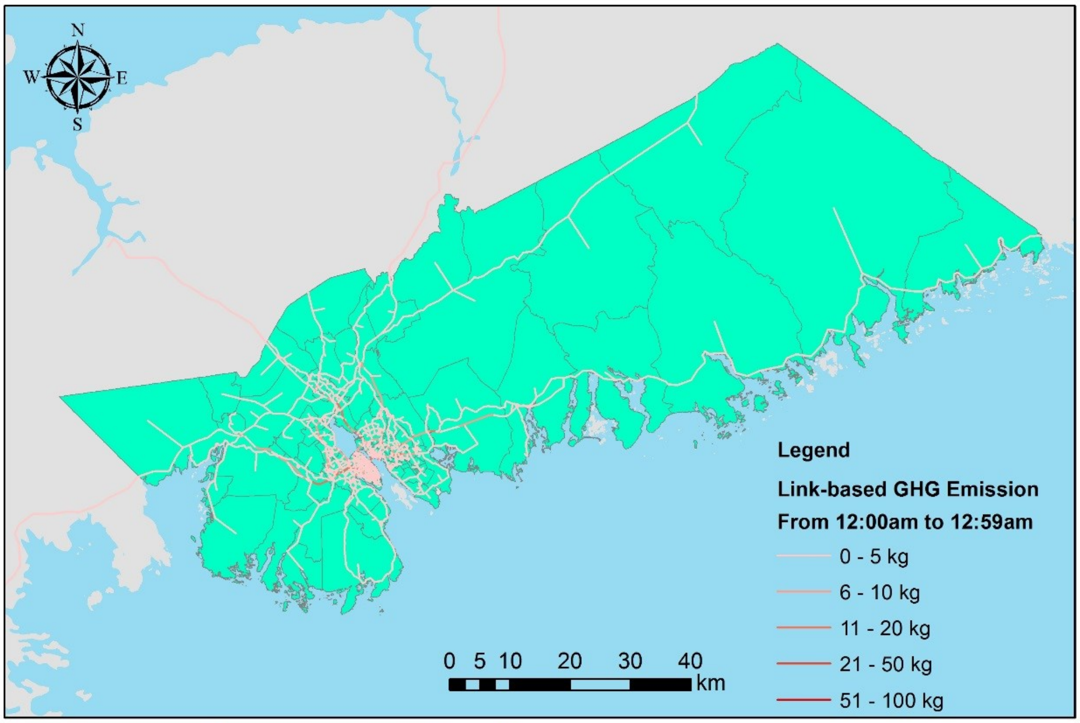

N
W
E
S
Legend
Link-based CO2 Emissions
From 8:00pm to 8:59pm
0 - 5 kg
6 - 10 kg
11 - 20 kg
21 - 50 kg
51 - 100 kg
0 5 10 20 30 40
km

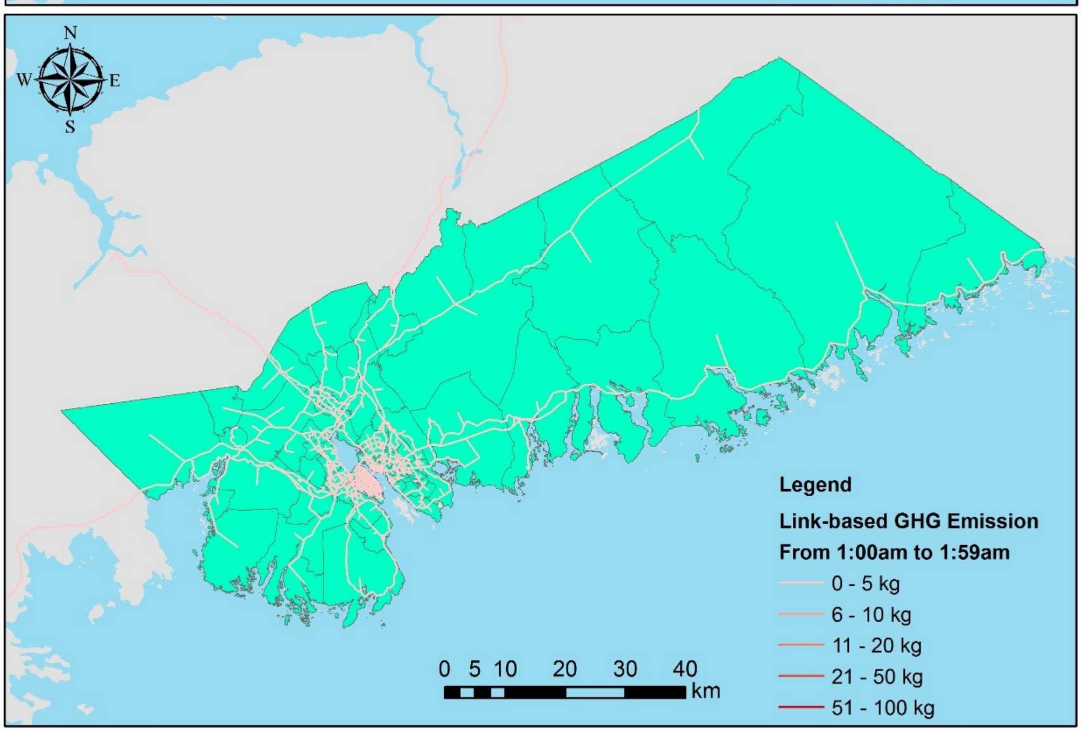

N
W
E
S
Legend
Link-based CO2 Emissions
From 9:00pm to 9:59pm
0 - 5 kg
6 - 10 kg
11 - 20 kg
21 - 50 kg
51 - 100 kg
0 5 10 20 30 40
km

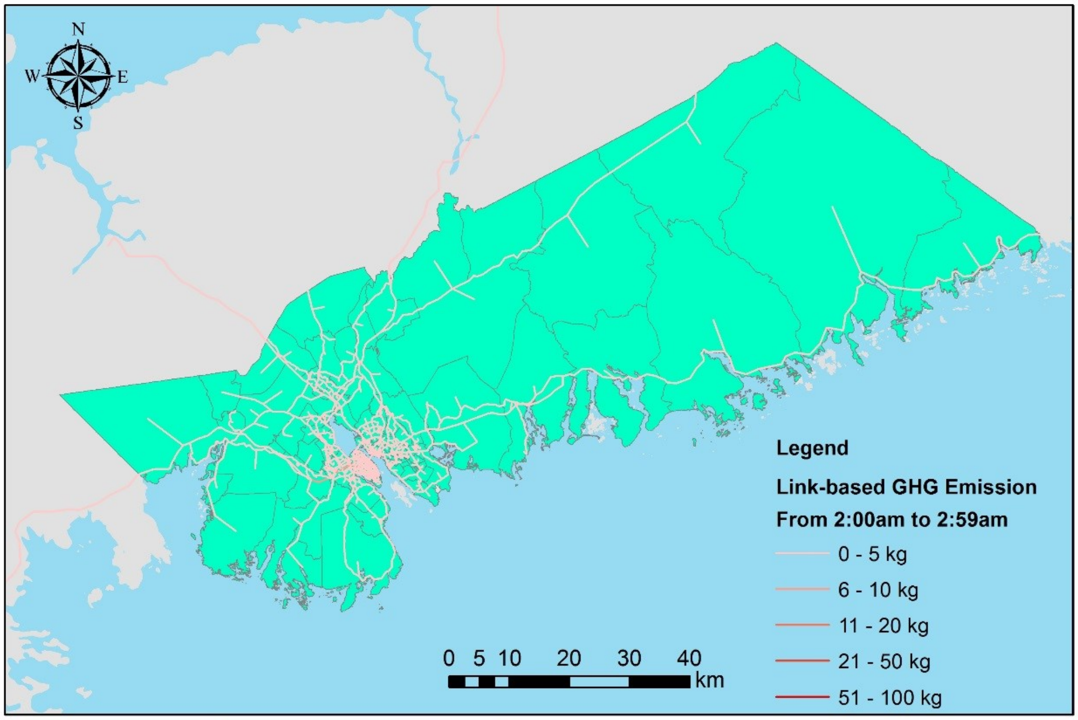

N
W
E
S
Legend
Link-based CO2 Emissions
From 10:00pm tp 10:59pm
0 - 5 kg
6 - 10 kg
11 - 20 kg
21 - 50 kg
51 - 100 kg
0 5 10 20 30 40
km

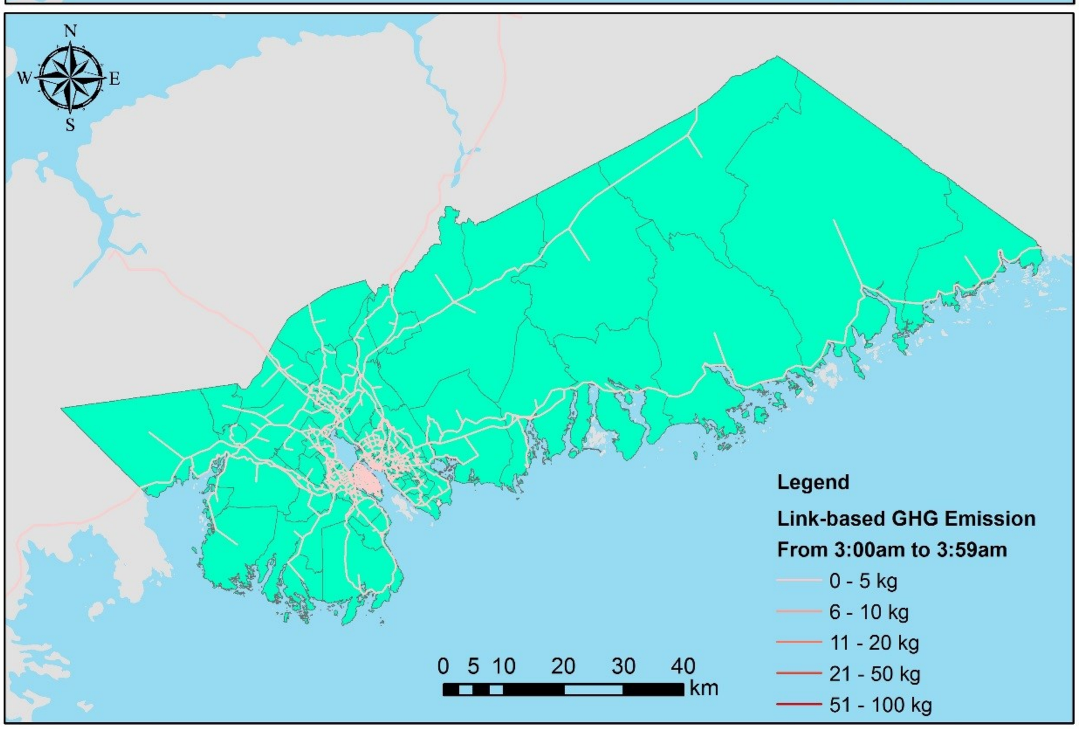

N
W
E
S
Legend
Link-based CO2 Emissions
From 11:00pm to 11:59pm
0 - 5 kg
6 - 10 kg
11 - 20 kg
21 - 50 kg
51 - 100 kg
0 5 10 20 30 40
km

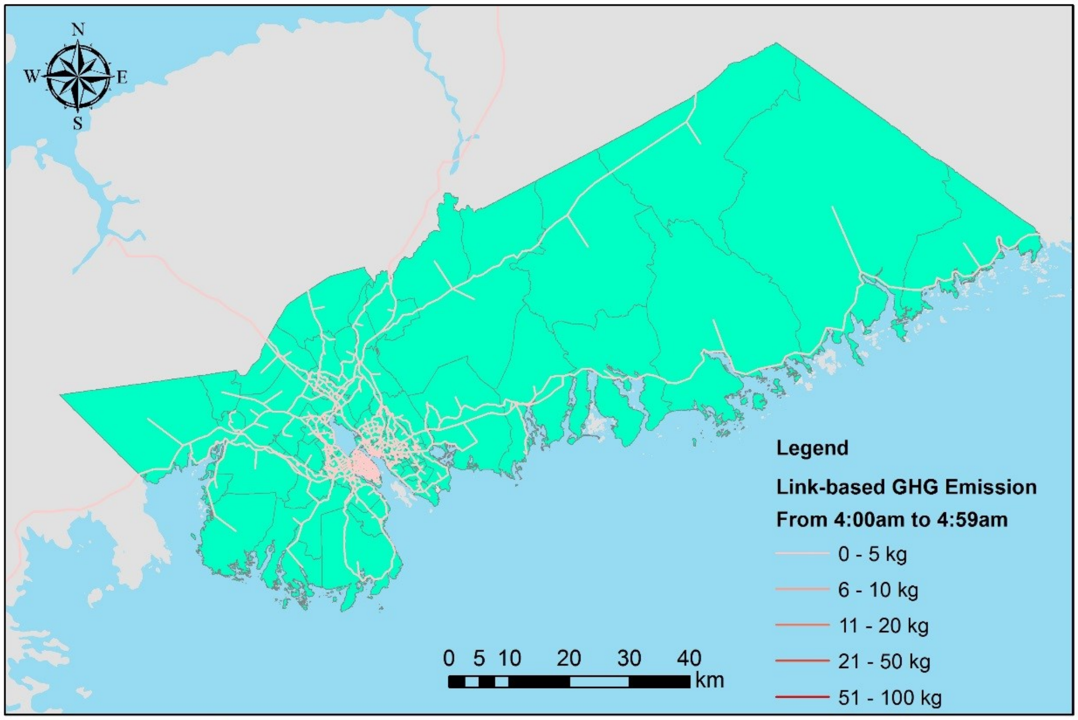
Appendix J 24-hour Link-based GHG Emission for the Model Year of 2016

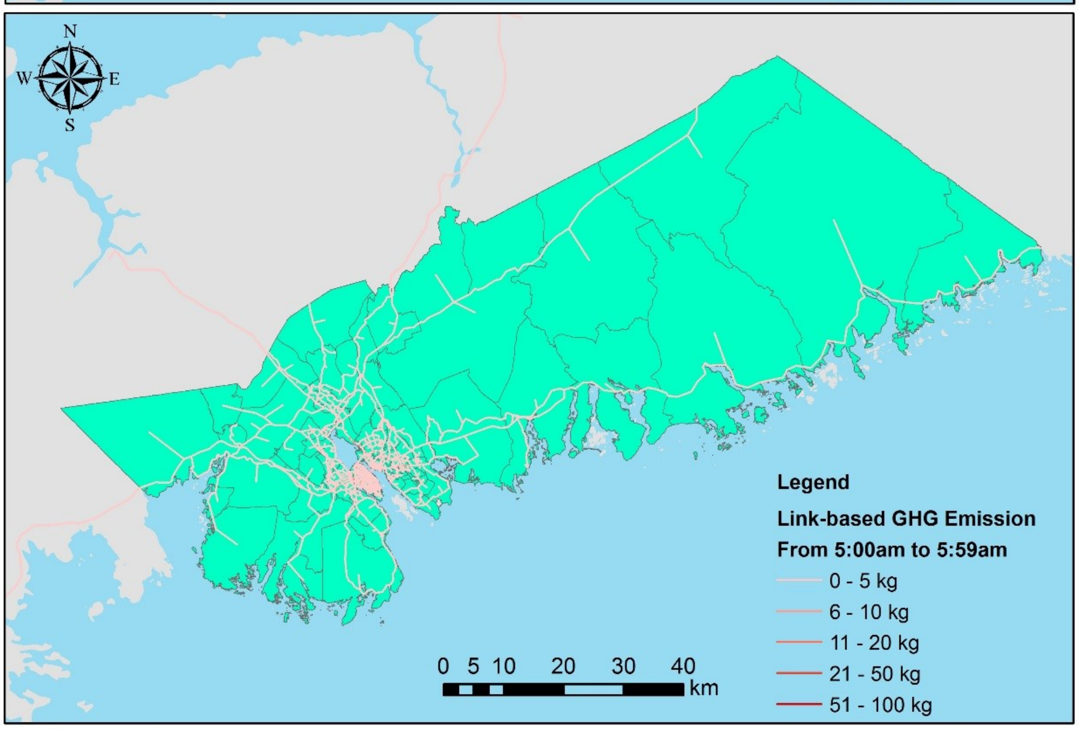


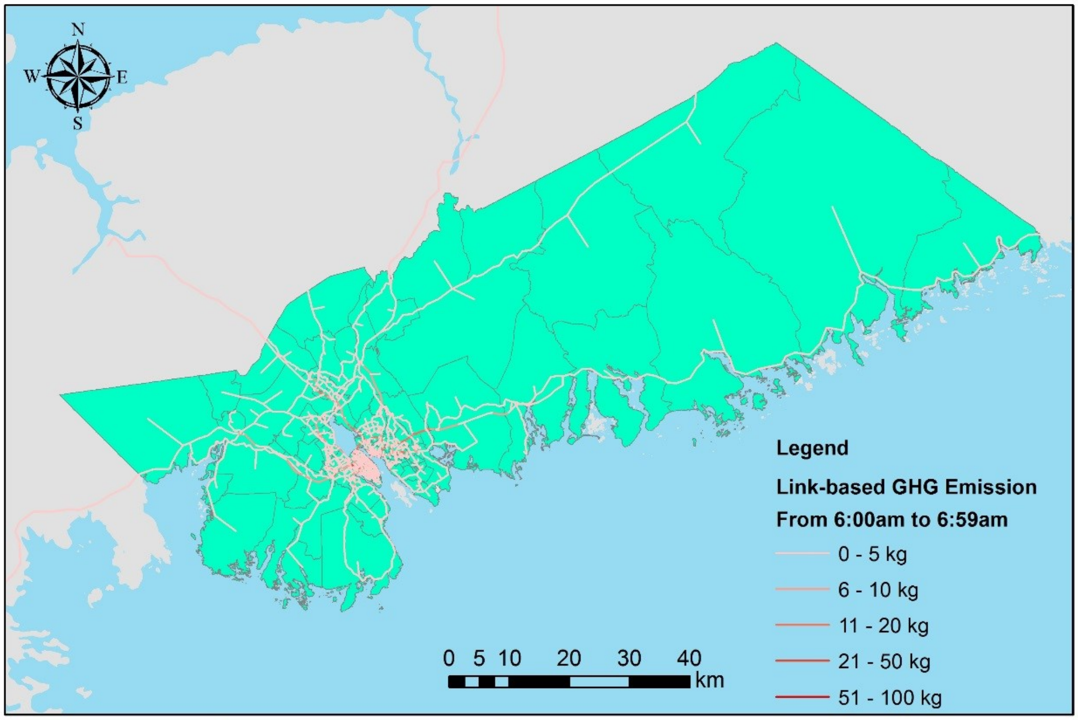


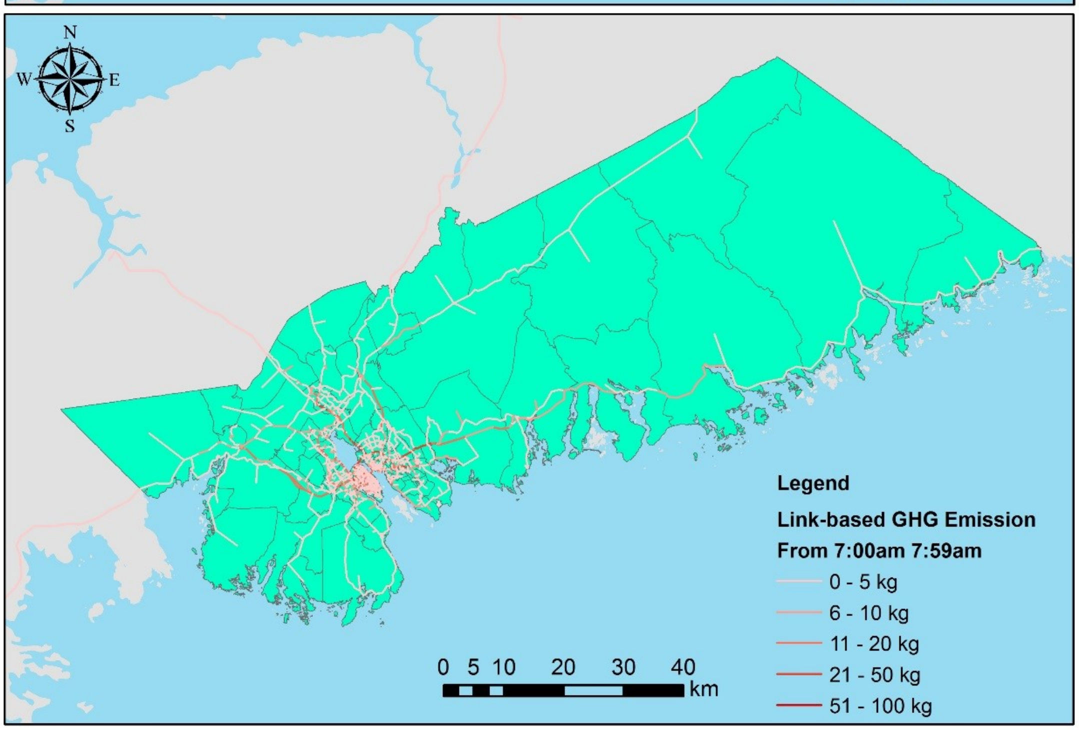

N
W
E
S
Legend
Link-based GHG Emission
From 2:00am to 2:59am
0 - 5 kg
6 - 10 kg
11 - 20 kg
21 - 50 kg
51 - 100 kg
0 5 10 20 30 40
km

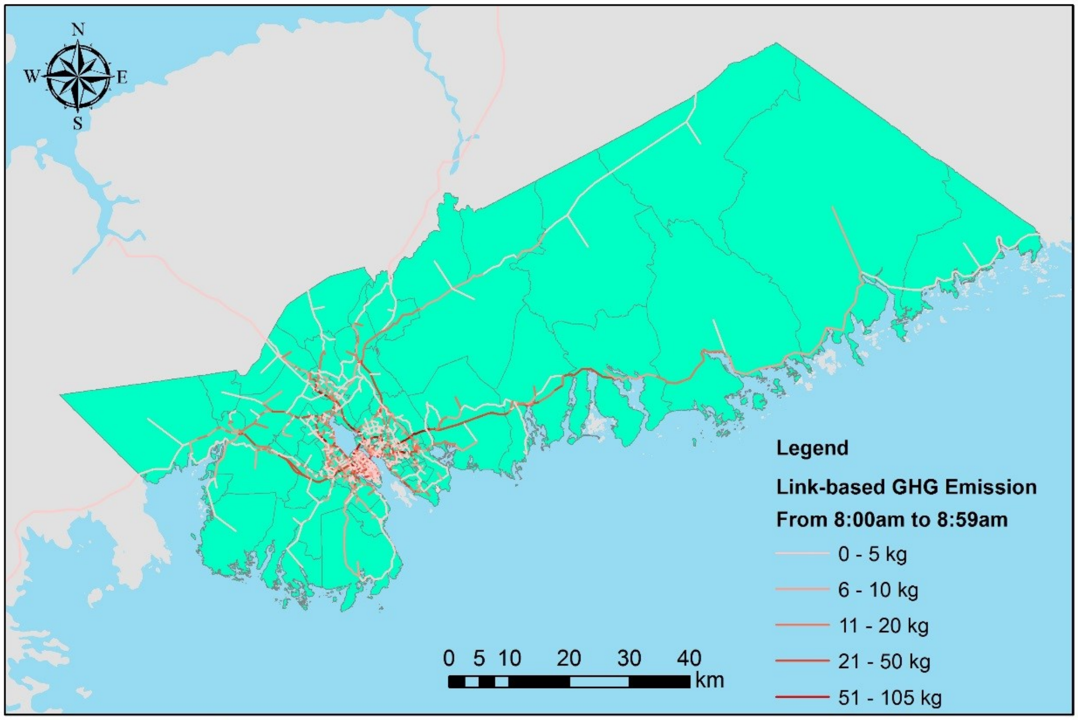

N
W
E
S
Legend
Link-based GHG Emission
From 3:00am to 3:59am
0 - 5 kg
6 - 10 kg
11 - 20 kg
21 - 50 kg
51 - 100 kg
0 5 10 20 30 40
km

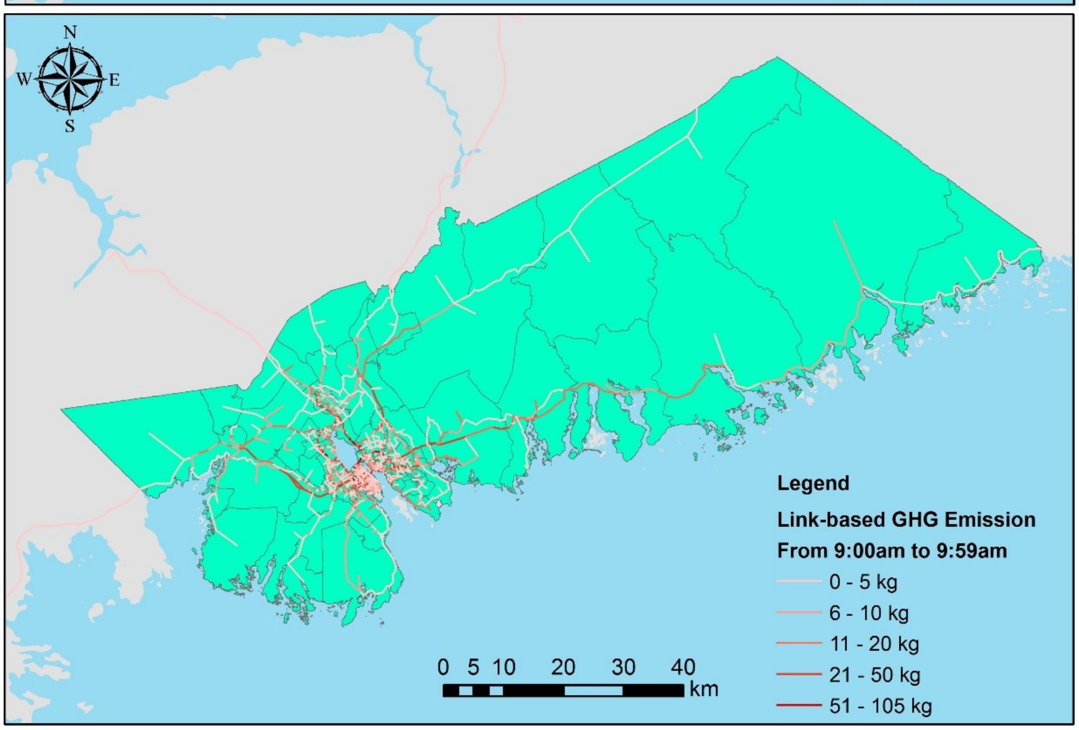

N
W
E
S
Legend
Link-based GHG Emission
From 4:00am to 4:59am
0 - 5 kg
6 - 10 kg
11 - 20 kg
21 - 50 kg
51 - 100 kg
0 5 10 20 30 40
km

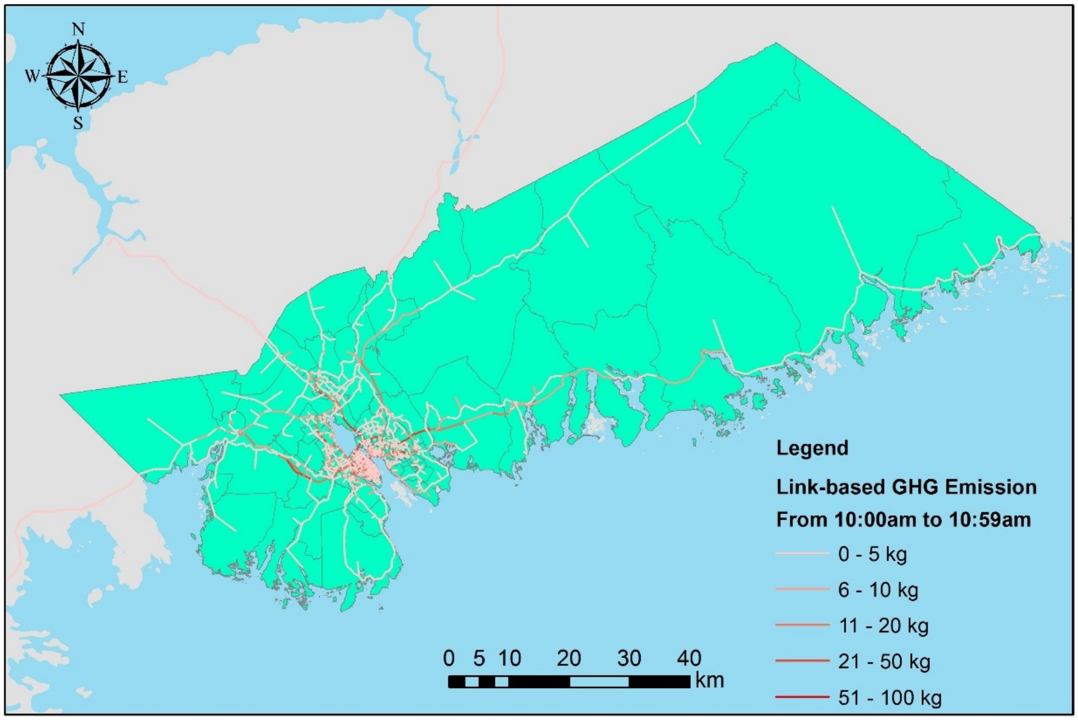

N
W
E
S
Legend
Link-based GHG Emission
From 5:00am to 5:59am
0 - 5 kg
6 - 10 kg
11 - 20 kg
21 - 50 kg
51 - 100 kg
0 5 10 20 30 40
km

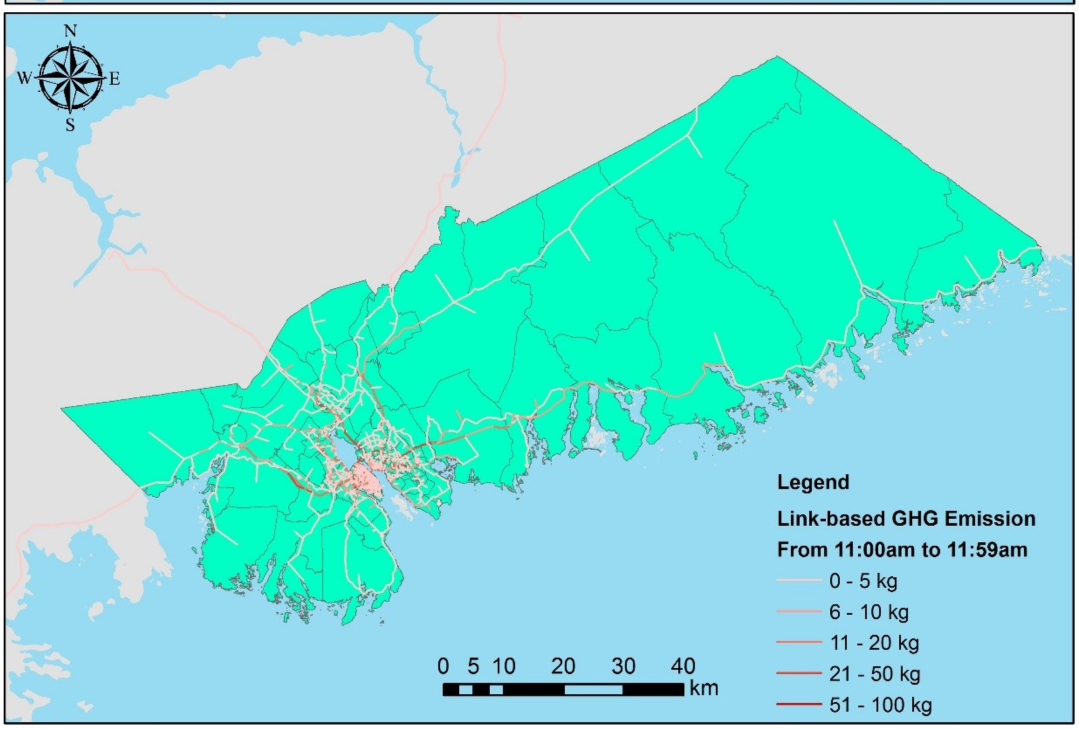

N
W
E
S
Legend
Link-based GHG Emission
From 6:00am to 6:59am
0 - 5 kg
6 - 10 kg
11 - 20 kg
21 - 50 kg
51 - 100 kg
0 5 10 20 30 40
km

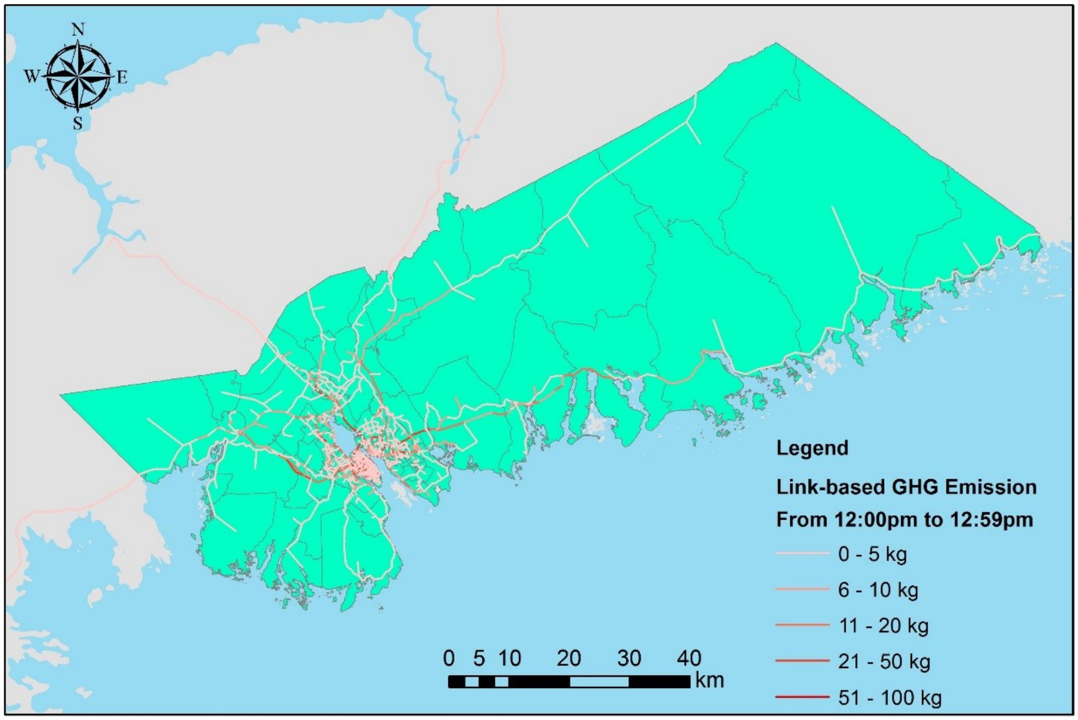

N
W
E
S
Legend
Link-based GHG Emission
From 7:00am 7:59am
0 - 5 kg
6 - 10 kg
11 - 20 kg
21 - 50 kg
51 - 100 kg
0 5 10 20 30 40
km

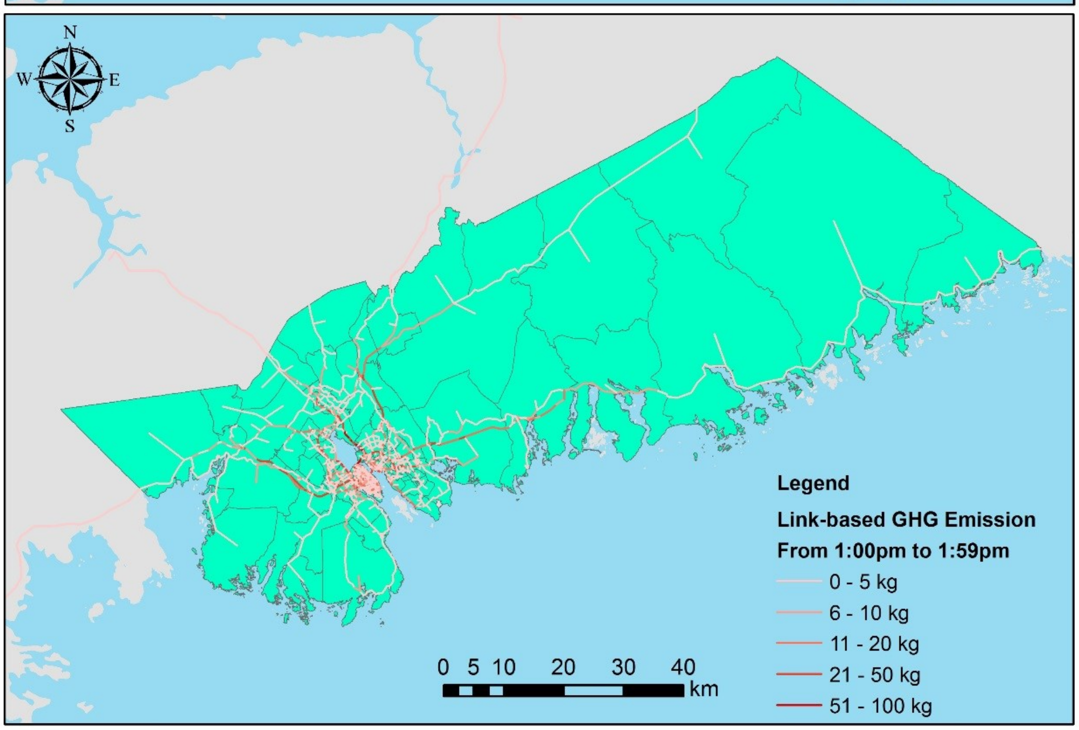

N
W
E
S
Legend
Link-based GHG Emission
From 8:00am to 8:59am
0 - 5 kg
6 - 10 kg
11 - 20 kg
21 - 50 kg
51 - 105 kg
0 5 10 20 30 40
km

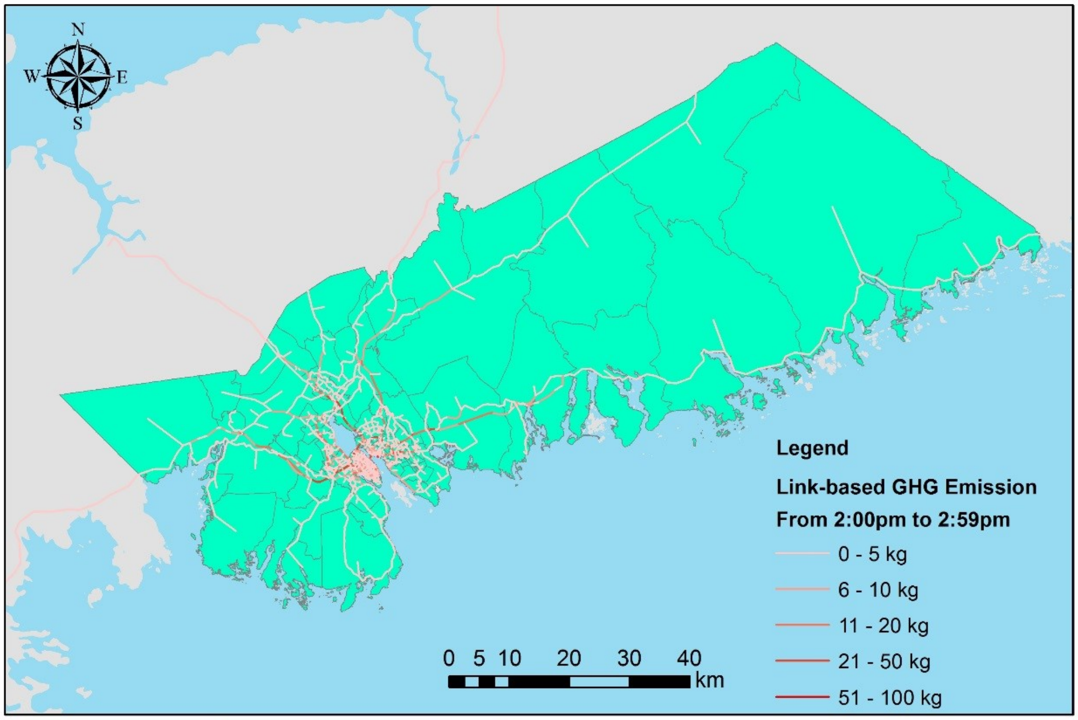

N
W
E
S
Legend
Link-based GHG Emission
From 9:00am to 9:59am
0 - 5 kg
6 - 10 kg
11 - 20 kg
21 - 50 kg
51 - 105 kg
0 5 10 20 30 40
km

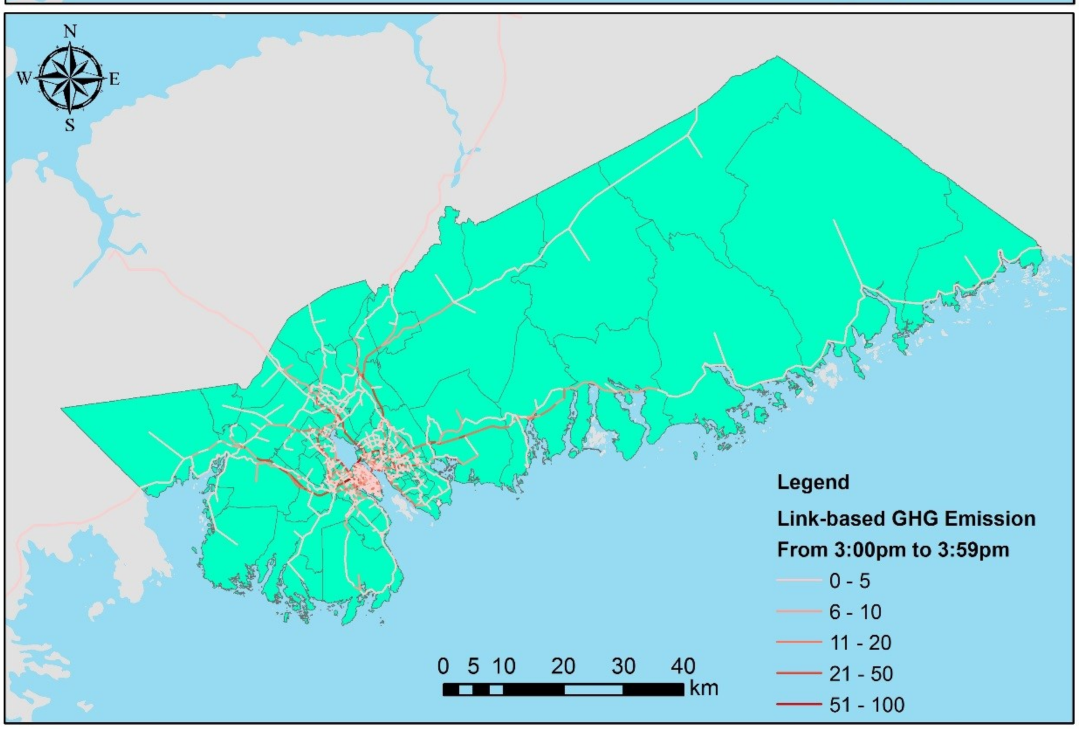

N
W
E
S
Legend
Link-based GHG Emission
From 10:00am to 10:59am
0 - 5 kg
6 - 10 kg
11 - 20 kg
21 - 50 kg
51 - 100 kg
0 5 10 20 30 40
km

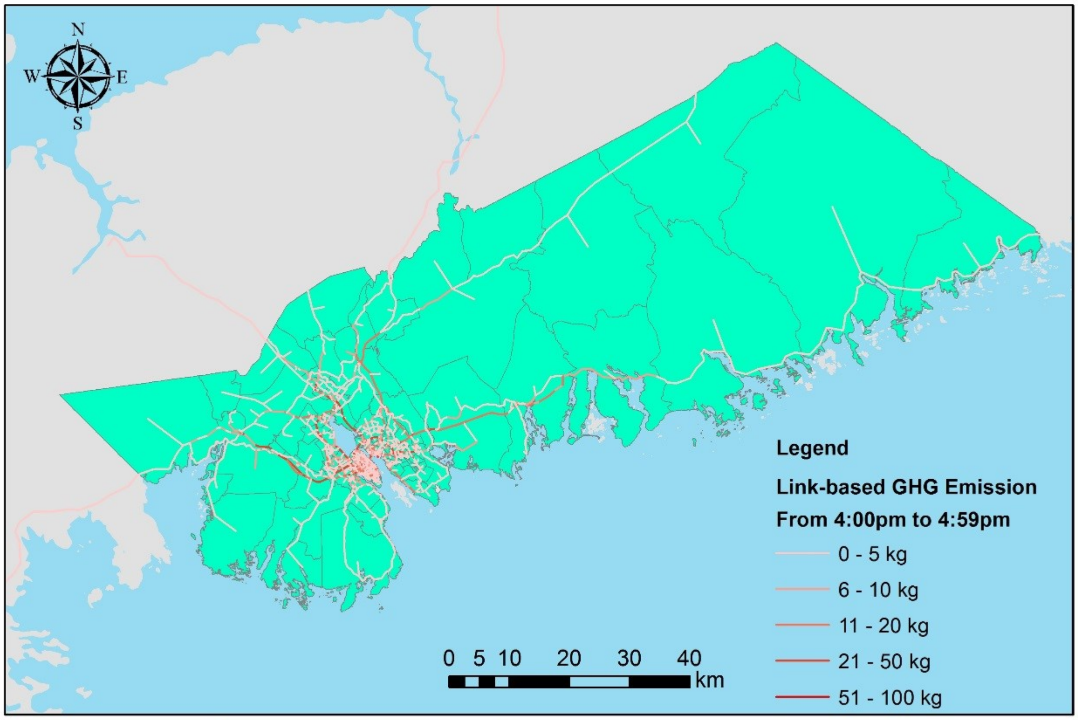

N
W
E
S
Legend
Link-based GHG Emission
From 11:00am to 11:59am
0 - 5 kg
6 - 10 kg
11 - 20 kg
21 - 50 kg
51 - 100 kg
0 5 10 20 30 40
km

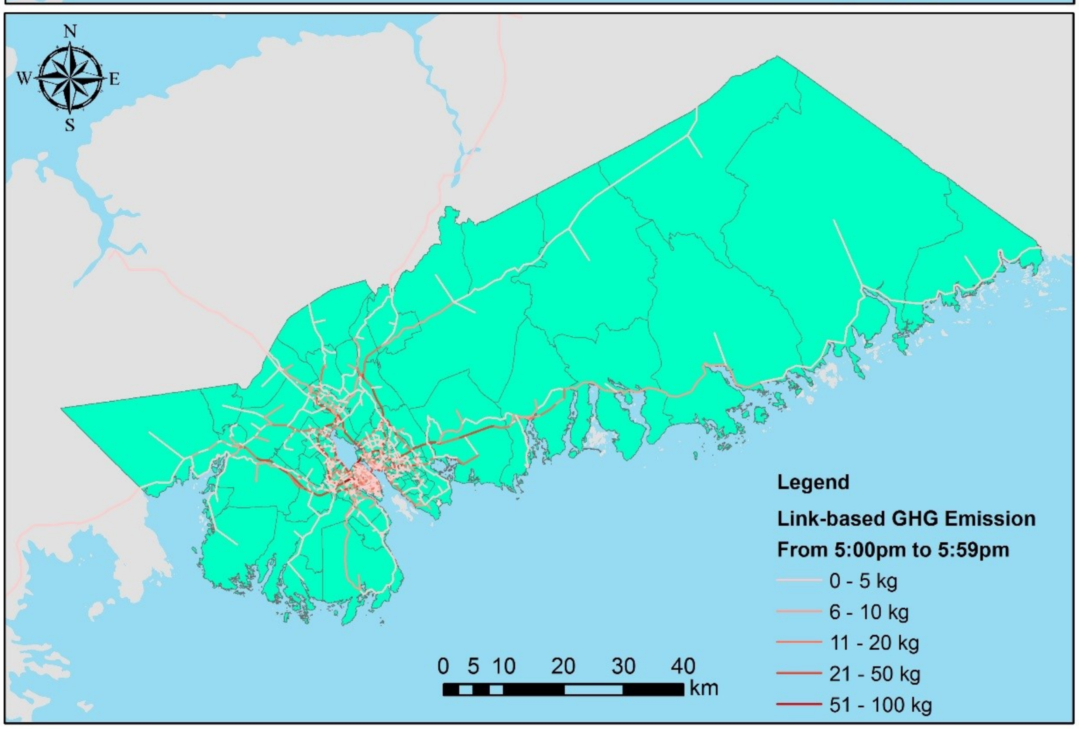

N
W
E
S
Legend
Link-based GHG Emission
From 12:00pm to 12:59pm
0 - 5 kg
6 - 10 kg
11 - 20 kg
21 - 50 kg
51 - 100 kg
0 5 10 20 30 40
km

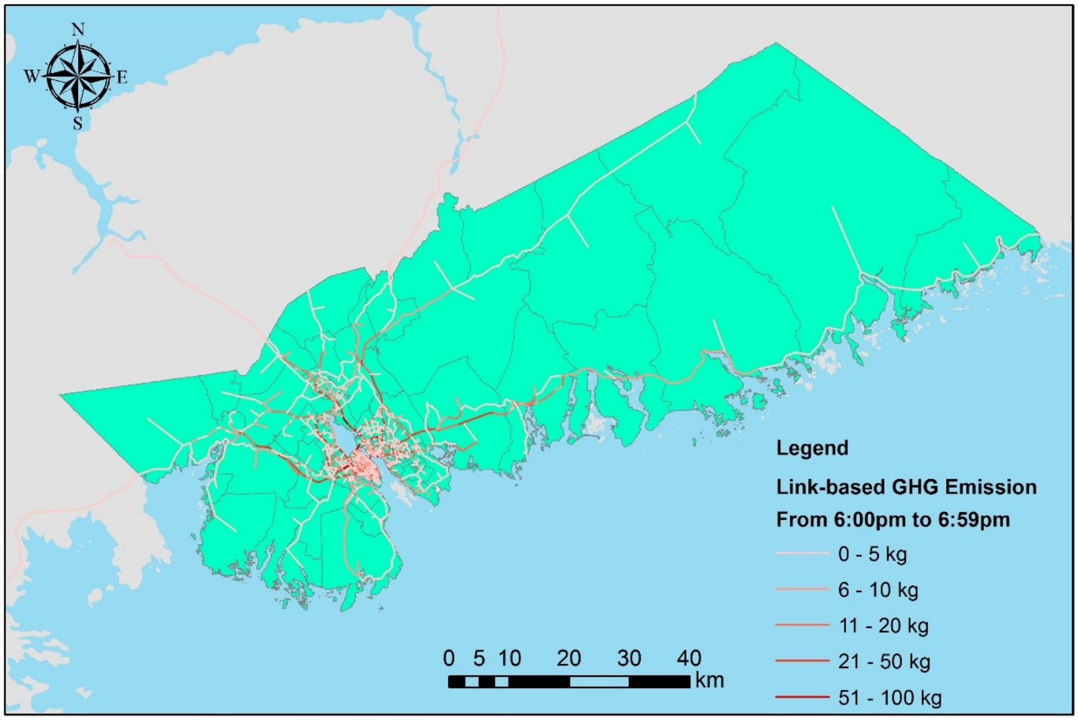

N
W
E
S
Legend
Link-based GHG Emission
From 1:00pm to 1:59pm
0 - 5 kg
6 - 10 kg
11 - 20 kg
21 - 50 kg
51 - 100 kg
0 5 10 20 30 40
km

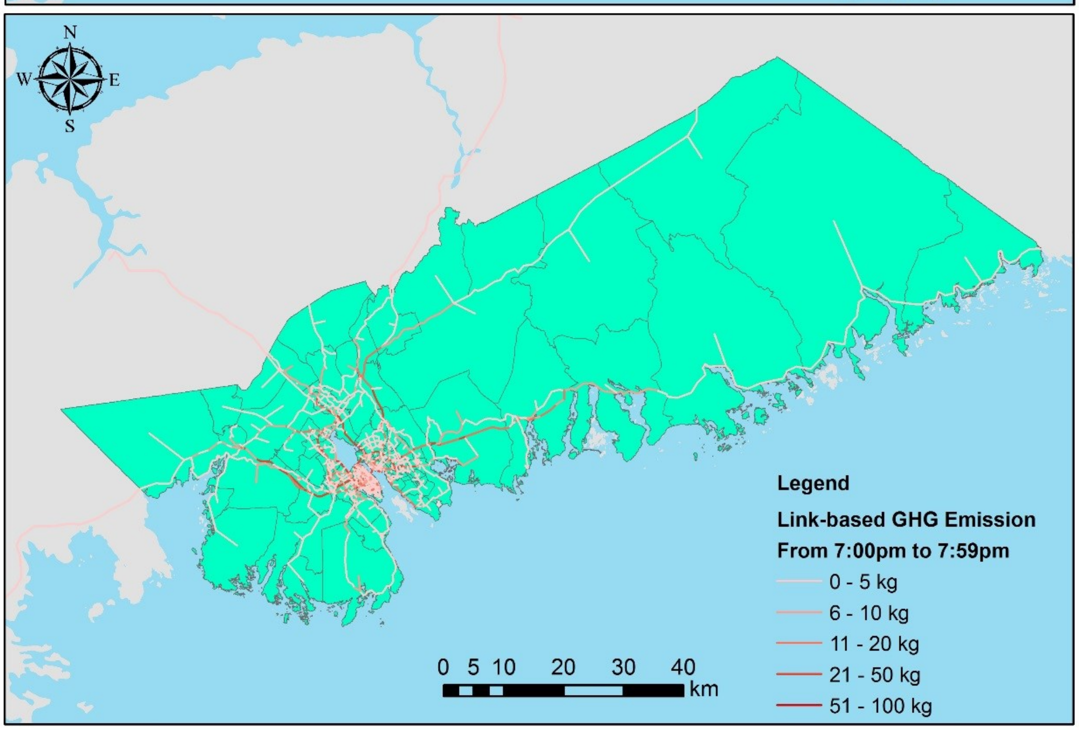

N
W
E
S
Legend
Link-based GHG Emission
From 2:00pm to 2:59pm
0 - 5 kg
6 - 10 kg
11 - 20 kg
21 - 50 kg
51 - 100 kg
0 5 10 20 30 40
km

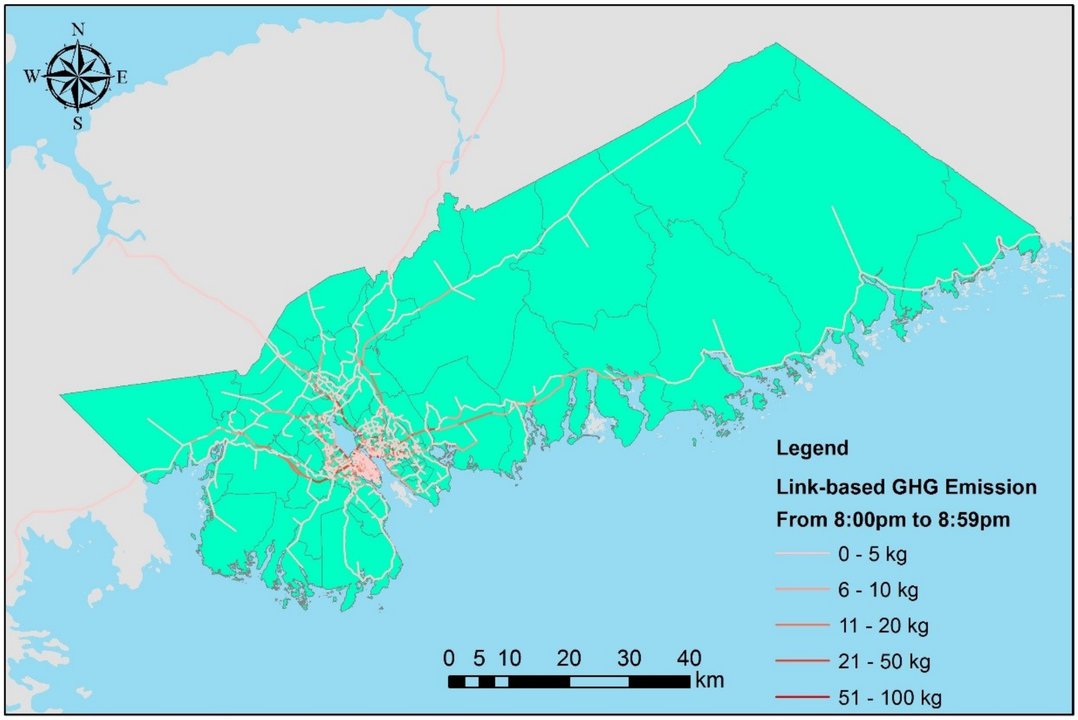

N
W
E
S
Legend
Link-based GHG Emission
From 3:00pm to 3:59pm
0 - 5
6 - 10
11 - 20
21 - 50
51 - 100
0 5 10 20 30 40
km

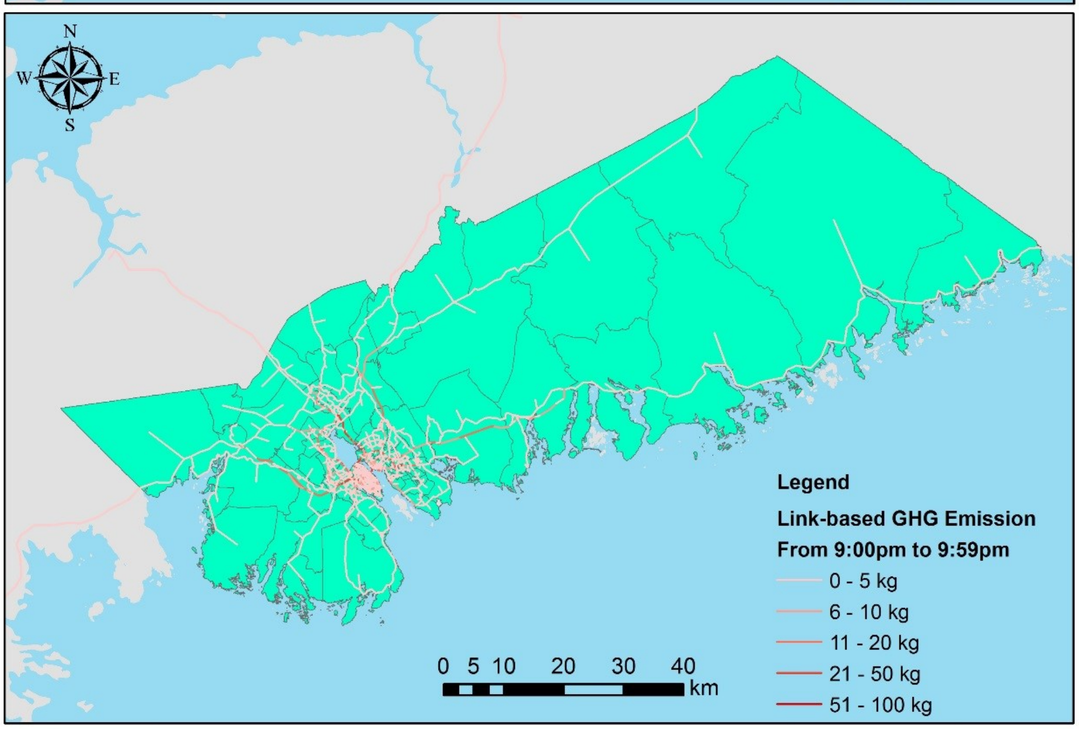

N
W
E
S
Legend
Link-based GHG Emission
From 4:00pm to 4:59pm
0 - 5 kg
6 - 10 kg
11 - 20 kg
21 - 50 kg
51 - 100 kg
0 5 10 20 30 40
km

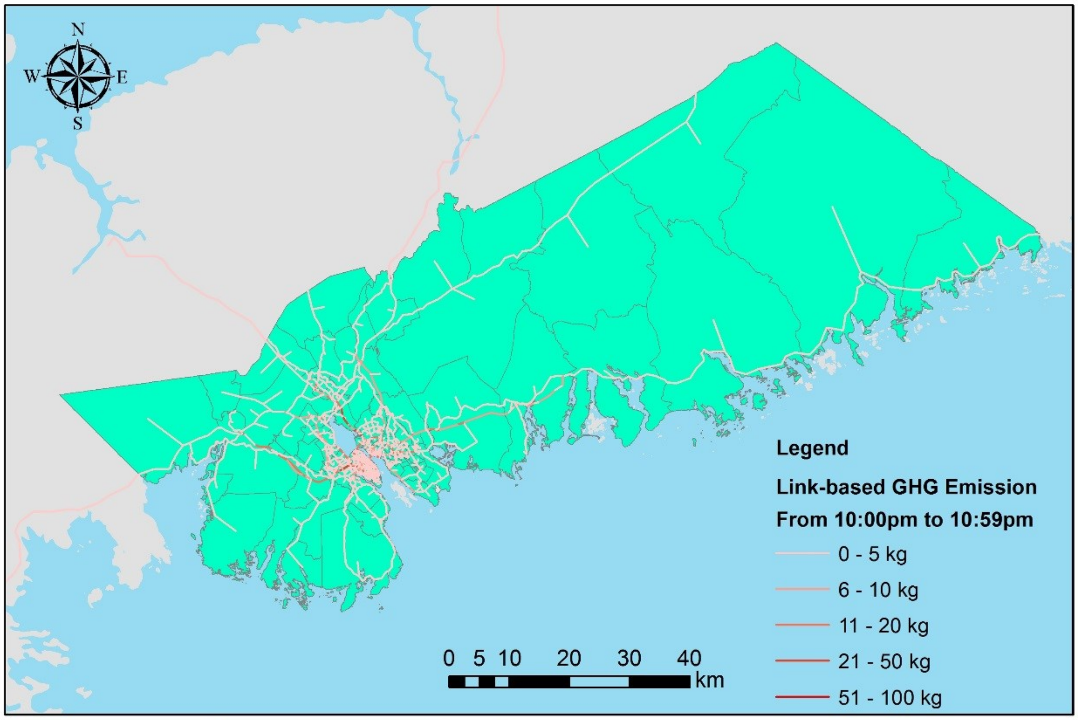

N
W
E
S
Legend
Link-based GHG Emission
From 5:00pm to 5:59pm
0 - 5 kg
6 - 10 kg
11 - 20 kg
21 - 50 kg
51 - 100 kg
0 5 10 20 30 40
km

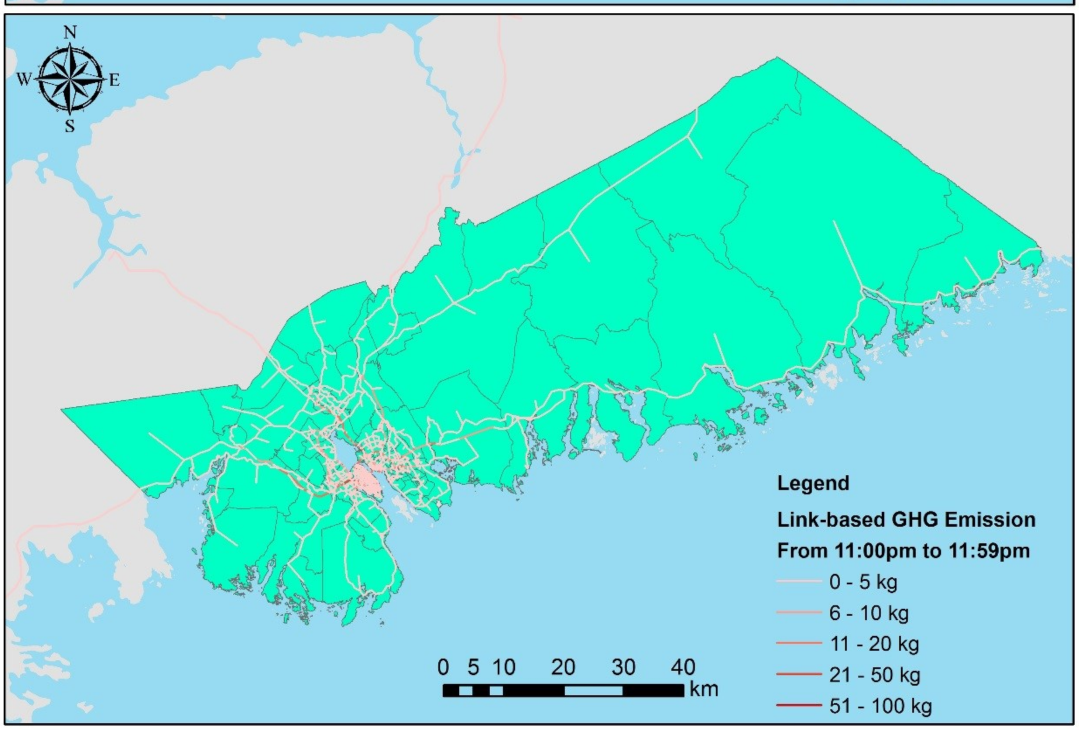

N
W
E
S
Legend
Link-based GHG Emission
From 6:00pm to 6:59pm
0 - 5 kg
6 - 10 kg
11 - 20 kg
21 - 50 kg
51 - 100 kg
0 5 10 20 30 40
km


N
W
E
S
Legend
Link-based GHG Emission
From 7:00pm to 7:59pm
0 - 5 kg
6 - 10 kg
11 - 20 kg
21 - 50 kg
51 - 100 kg
0 5 10 20 30 40
km


N
W
E
S
Legend
Link-based GHG Emission
From 8:00pm to 8:59pm
0 - 5 kg
6 - 10 kg
11 - 20 kg
21 - 50 kg
51 - 100 kg
0 5 10 20 30 40
km


N
W
E
S
Legend
Link-based GHG Emission
From 9:00pm to 9:59pm
0 - 5 kg
6 - 10 kg
11 - 20 kg
21 - 50 kg
51 - 100 kg
0 5 10 20 30 40
km


N
W
E
S
Legend
Link-based GHG Emission
From 10:00pm to 10:59pm
0 - 5 kg
6 - 10 kg
11 - 20 kg
21 - 50 kg
51 - 100 kg
0 5 10 20 30 40
km


N
W
E
S
Legend
Link-based GHG Emission
From 11:00pm to 11:59pm
0 - 5 kg
6 - 10 kg
11 - 20 kg
21 - 50 kg
51 - 100 kg
0 5 10 20 30 40
km